4.—THE GEOLOGY AND PETROLOGY OF PART OF THE TOODYAY DISTRICT, WESTERN AUSTRALIA.*

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I. INTRODUCTION.

The area which measures about 12 miles in an East-West direction, by three to four miles in a North-South direction, lies several miles to the south of the town of Toodyay, which is situated about 50 miles north-east from Perth. It is occupied almost entirely by a series of crystalline schists to which the name "Jimperding Series" has been given (Clarke, 1930, p. 167) and which is believed to be of an early Pre-Cambrian age. This series comprises pelitic and psammitic metasediments with intercalated basic and acid igneous bands. A study of the pelitic members shows that over the whole area mapped the rocks lie within the sillimanite zone.

This series has been intruded by granite (and its associated aplitic and pegmatitic dykes) and afterwards by a series of quartz dolerite and rare ultrabasic dykes—none of these igneous intrusions has metamorphosed the older rocks.

The only rocks of later age than the quartz dolerite series are of superficial character—laterites (duricrust, Woolnough, 1930) and recent alluvial deposits. The duricrust occurs at an elevation of about 900 feet above sea-level, and has been developed over all the older rocks, even the extremely siliceous quartzites. Neither it nor the alluvial deposits will be considered in this paper, which deals with the Pre-Cambrian rocks.

A brief account of the rocks from the western part of this area has been published (Prider, 1934, pp. 1–16) but, other than this, there is no account of the petrology of any of these Pre-Cambrian rocks. Simpson has described a number of the minerals occurring in the metamorphic rocks of the Darling Range, several from the area at present under consideration, viz., andalusite from Jimperding (Simpson, 1928, p. 50), sillimanite, also from Jimperding (Simpson, 1936, p. 10), and grossularite from Key Farm (Simpson, 1937, p. 32).

Clarke (1930, p. 167) shows that the Jimperding Series forms the greater part of the northerly extension of the Darling Range. From the vicinity of Toodyay, the rocks extend in a belt which has been traced as far north as the Irwin River District (about 200 miles north from Toodyay) and Ninghanboun Hills (Simpson, 1931, p. 138). I have examined the rocks in the Irwin River District and they appear to be essentially the same as those developed at Toodyay.

To the south of Toodyay the Jimperding Series has been traced through Clackline (the series exposed here is the upper portion of the Jimperding Series) to York, a distance of 30 miles.

Previous to the publication of a paper by Forman (1937, pp. xvii.–xxvii.), the Jimperding Series had been regarded as the oldest formation in the Western Australian Pre-Cambrian shield. Forman (1937, p. xxv.) regards the "greenstones" of the Kalgoorlie Series as being older than the Jimperding (= Yilgarn) Series. Feldtmann (1919) describes a greenstone series at Bolgart (situated approximately 20 miles north from Toodyay) and correlates it with the Kalgoorlie Greenstone Series and Forman considers that these rocks probably underlie the Jimperding Series (1937, p. xxvi.). I have examined slices of some of the Bolgart rocks collected by Mr. R. W. Fletcher and find, in them, the counterpart of rocks occurring as xenoliths in the granitic gneisses in the Toodyay District—this would be confirmatory evidence that the Jimperding Series is younger than the Bolgart "greenstones," were it not that similar rocks are interbedded with the metasediments of the Jimperding Series.

This paper has been subdivided into two main sections, thus :—

I. The Geological Structure.

II. Petrology—

(A) The Jimperding Series.

(B) The later igneous intrusions.

In view of the variety of rock types developed in the area, theories of origin of each main group are discussed immediately after the description of typical members of that group and these theories are briefly recapitulated at the end of the paper.

II. THE GEOLOGICAL STRUCTURE OF THE AREA.

The regional strike throughout the Pre-Cambrian rocks in South-Western Australia is N.W.–S.E. In the area under consideration, there is a distinct departure from this N.W. regional strike, for, over a great part, the strike is more nearly E.–W.

A Pre-Cambrian metasedimentary series (the Chittering Series) has been described by Miles (1938) from the Chittering Valley, some 15 miles west from the Toodyay area. The dominant strike of these rocks is N. to N.W. These rocks are similar in character to the Toodyay rocks, but no information regarding the relationship of the Chittering and Jimperding Series is available, as the country between Toodyay and the Chittering Valley has never been geologically examined.

South of the Toodyay area, the Jimperding Series has been noted at Clackline and York and in both places the dominant strike is in a northerly direction.

It will be seen, therefore, that the Toodyay area is one of abnormal strike —unfortunately, field work has not covered a sufficient area to warrant any definite conclusions being drawn as to the true character of the structure, but in the following pages the structure is described so far as it is known.

From the geological map of the area (Plate I.), it will be seen that the whole area, except the S.W. corner, is occupied by a conformable series (note, however, that at a position about 300 chains W. and 80 chains N. of datum, the outer band of granitic gneiss appears to transgress the quartzite-hornblende schist-mica schist bands). The main structural features can be seen best in the accompanying sketch map (figure 1), which has been simplified from the more detailed, larger-scale, map.

Two wide bands of granite gneiss are interbedded with the metasediments —the banding everywhere conforming to that of the metasediments (except in the one place noted above). In the south-west part of the area, the boundary between granite gneiss and metasediment on the western side strikes nearly E.–W., but farther east the strike swings round to a south-easterly direction. The northern boundary of this upper gneiss band does not run parallel to the southern boundary, except in the westernmost part of the area. Towards the centre of the area it swings to the N.E. for a distance of approximately three miles and then turns sharply to a S.S.E. trend. The outer granitic gneiss (termed " Lower Gneiss " in figure 1) runs more or less parallel to the

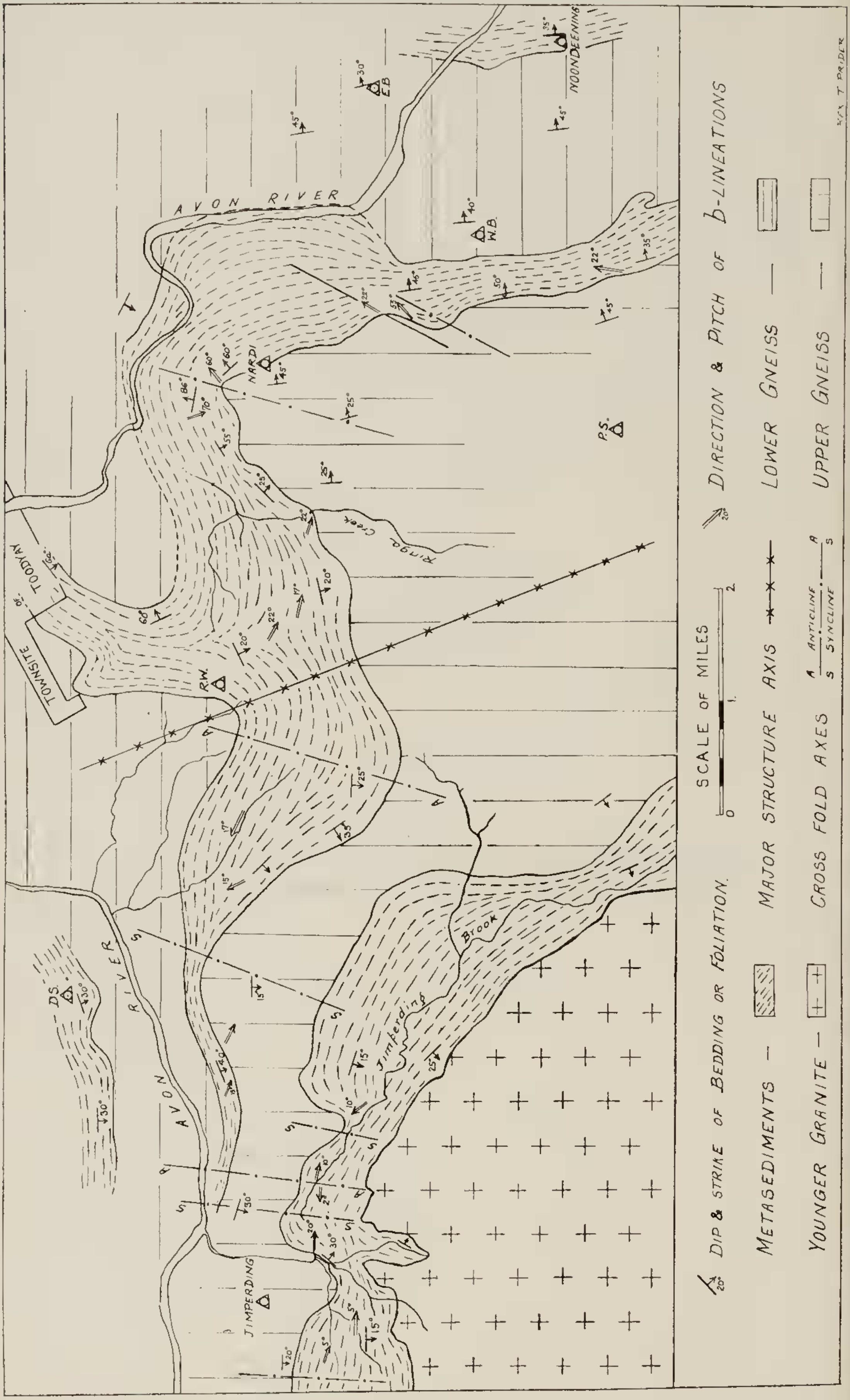

Fig. 1.
Structural Sketch Map of the Toodyay Area.

northern boundary of the upper granite gneiss and is bounded on both sides by metasediments, the dip and strike of which conform to that of the gneiss.

Regarding the dip of these rocks—in the western half of the area the dip is constantly south at amounts ranging from 15° to 40° ; in the centre of the area the general dip is at fairly flat angles to the south-east but there is a considerable amount of minor folding in the metasediments in this part ; at the place where the strike suddenly changes to the S.S.E. in the N.E. part of the area the dips are very steep to the south, and thereafter fairly steep to the east.

From the field mapping the structure of this area is interpreted as :—

A major anticlinal structure (*see* figure 1), the axis of which traverses the centre of the area in a direction striking approximately N.N.W. and pitching to the S.S.E., which has, on its eastern limb, a recumbent syncline with its axial plane striking N.N.W. and dipping towards the east at approximately 60°. The axis of this fold also pitches to the south. The sequence as it appears in the eastern part of the area is therefore inverted. These structures are illustrated on the cross sections appearing with the geological map in Plate I.

This idea of the structure of the area would receive considerable support if it could be proved that the beds of the north and north-east parts of the area were older than those of the south-western parts. Up to the present, however, there is very little evidence other than that afforded by occasional drag folds, for determining the age relations of these rocks. Complete recrystallisation has almost obliterated graded bedding and similar structures which might have afforded criteria for determining the stratigraphical succession. (Some obscure current bedding structures have been noted but no certain interpretation of these was possible). All the rocks are in the sillimanite zone, and consequently grade of metamorphism affords no information as to the succession. Read (1936, p. 473) has pointed out that the abundance of andalusite in narrow pelitic bands may be due to graded bedding—the lower gritty postions of the band being almost free from andalusite, which becomes more abundant in the upper more pelitic part of the band, and he has applied this method to determining the stratigraphical succession in the Dalradian rocks at Banff. In the area at present under discussion this variation in size and abundance of andalusite in the upper pelitic rocks of the series is not present. As far as can be seen the rocks throughout this band are fairly uniform in composition. There is, as will be shown later, a constant variation in the development of the andalusite in this band, but this extends over a considerable width and is not due to any variation in the argillaceous components of the original sediment, but rather to a variation in the temperature conditions to which the rocks have been subjected.

Drag folded structures in the quartzites at a position 140 chains east and 225 chains south of datum indicate that the easterly dipping metasediments at that locality are on the western limb of an anticline overturned to the west and that the sequence in this vicinity in inverted.

If, as suggested by the drag folds at 140 E., 225 S., the rocks of the northern and eastern part of the area are older than those to the south-west (if they are not, the whole succession over the greater part of the area surveyed must be inverted), then the order of succession, with approximate thickness of the individual beds is as follows :—

Upper	Andalusite-muscovite schist	> 250′
	Quartzite	500′
	Upper Granite gneiss (with rare basic igneous and meta-sedimentary xenoliths)	1900′
	Quartzite	110′
	Hornblende schist	40′
	Quartzite	570′
	Sillimanite schist	100′
	Quartzite	375′
	Lower Granite gneiss (characterised by the presence of basic igneous and sedimentary xenoliths)	5,400′
	Quartzite	650′
	Hornblende schist	35′
Lower	Quartzite	Unknown

These rocks form the Jimperding series and are intruded in succession by the following :—

1. Coarse non-foliated microcline granite.
2. Pegmatites, garnet aplites, and garnet muscovite granites.
3. Quartz dolerites.
4. Serpentinised ultrabasic sills and dykes.

The age relation of the quartz dolerite series and ultrabasics is not at present known.

Large scale faulting in the metamorphic rocks has been noted in several places, the most notable being in the part of the area situated about one and a-half miles east from Nardi Trig Station where a faulted block of the metamorphics is found. This block has suffered a displacement of approximately one and a-half miles along the fault plane (see E.–W. section through datum on Plate I.).

The lithology and structure of the area are reflected in the topography. The metasedimentary areas are all rough country, whereas the granite gneiss and granite areas are comparatively smooth. The main stream, the Avon River, as will be seen from the geological map (Plate I.) follows the structure very closely, and its main tributary (the Jimperding Brook) behaves in a similar fashion in the upper part of the series.

The distribution of the later quartz dolerite dykes is interesting in connection with the structure of the area. A glance at the geological map shows that they trend generally in a N.N.W.-S.S.E. direction. There are some exceptions to this, but the greater number of dykes have this trend. They have apparently come up along lines of weakness approximately parallel to the tectonic "strike" (or tectonic axis).

III. PETROLOGY.

A.—*The Jimperding Series.*

The metasedimentary members of this series, viz., the quartzites and mica schists will be described first and the igneous members (plagioclase amphibolites and granite gneisses) later.

(1) *The Quartzites.*

These are mostly coarse grained almost pure quartz rocks occurring in well defined bands. In the field they have a well bedded, flaggy appearance and are much jointed.

On all the bedding surfaces a well marked lineation (figure 2), due to elongation of mica flakes, is visible. This lineation is often accompanied by a corrugation of the surfaces of the quartzite flags. Unfortunately the significance of this lineation as pointed out by Phillips (1937, p. 591) was not appreciated at the time when the original field survey (made prior to 1936) was being carried out, but certain significant localities within the area have since been re-examined and the direction and pitch of these lineations noted. The light that these observations have thrown on the geological structure will be given in a later section.

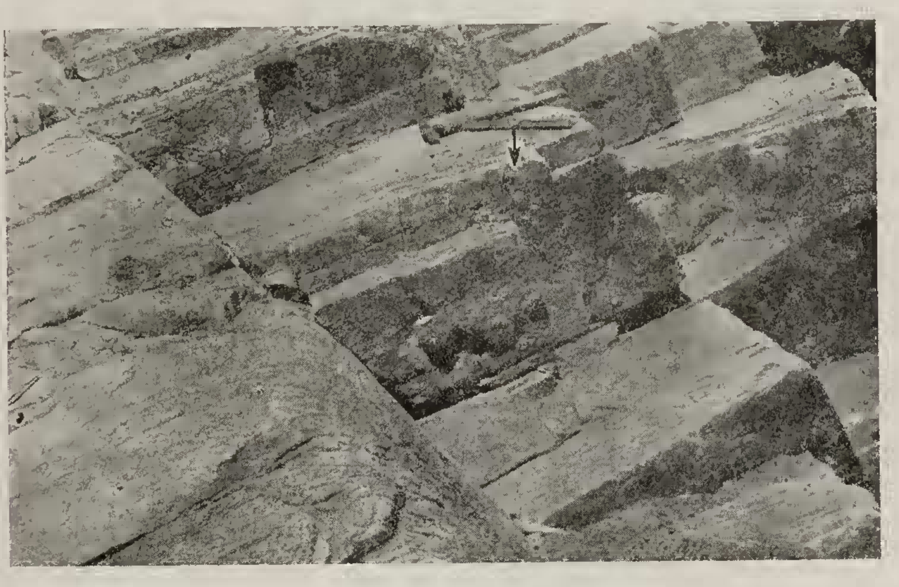

Fig. 2.

Quartzite outcrop in Gorge Creek, near Key Farm, Toodyay, showing well marked b-lineations. The clinometer indicates the strike and rocks dip towards the observer in the direction of the arrow. The hammer handle lies in the direction of the b-lineations which pitch to the left-hand side of the outcrop. The well-marked jointing of the quartzites is a noticeable feature. (Reproduced from "Junior Geology" by E. de C. Clarke and L. F. Hanrahan, by kind permission of the University of Western Australia Textbooks Board.)

The structure in all the specimens examined microscopically, is similar, viz., coarsely granoblastic consisting almost entirely of irregular interlocking grains of quartz. All signs of clastic structure have been completely obliterated by recrystallisation. In all the rocks examined there is slight undulatory extinction, but no other signs of crushing in the quartz. A pale greenish chrome muscovite is the most common constituent other than quartz, and is present in all the specimens examined. Occasionally narrow seams up to 2 inches thick of this mica are interbedded with the quartzites. Felspar (mainly microcline with a little oligoclase) is a common constituent, but rarely exceeds 5 per cent of the rock. Minor minerals present in varying amount, are magnetite, apatite, rounded pink zircons, biotite, and rutile. These "heavy" minerals are occasionally concentrated into bands (figure 4B).

In the earlier examination of these rocks from the Jimperding Area, it was thought possible to distinguish the various quartzite bands by means of the minor constituents (Prider 1933, p. 7). Extension of the survey and an examination of a greater number of the lower quartzites has indicated that, while possible to distinguish between the uppermost horizon and the bands in the lower part of the series, these lower members could not be distinguished from one another.

In this paper, therefore, the quartzites will be considered in two main groups :—

(*a*) The upper quartzite (No. 5 quartzite of the earlier paper).

(*b*) The lower quartzite horizons.

(*a*) *The Upper Quartzite* is characterised by the mode of occurrence of chrome muscovite and almost complete absence of felspar. These rocks are all even, coarse-grained types, consisting almost wholly of quartz, in which the average grain size is of the order of 3 mm. diameter, although much coarser varieties are often encountered. The remarkable evenness and coarseness of grain indicate the high degree of metamorphism to which these rocks have been subjected (Harker, 1932, p. 67).

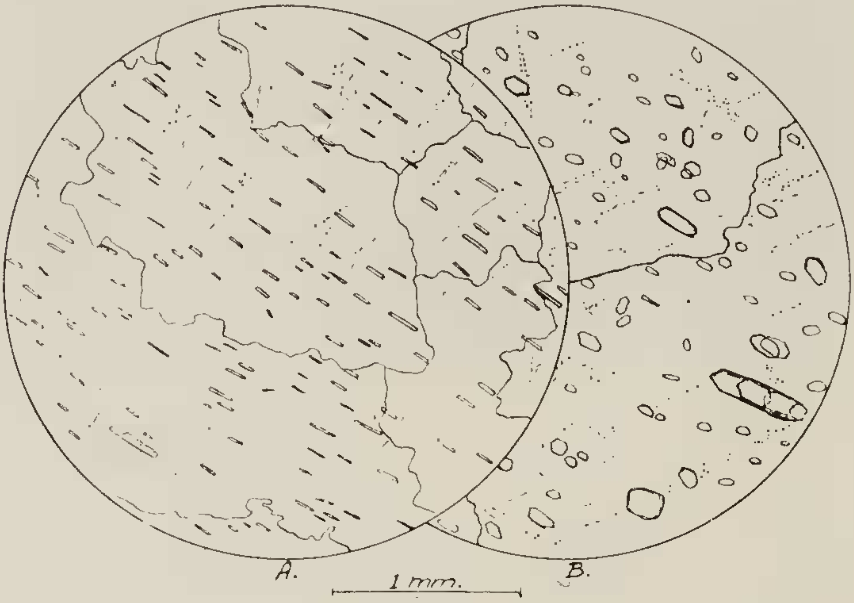

Fig. 3.

A. Micaceous quartzite. Section perpendicular to bedding. Shows the coarse granoblastic structure and parallel oriented rods of chrome-muscovite.

B. Micaceous quartzite. Section parallel to bedding showing tendency of idioblastic mica to be elongated in a common direction (= direction of lineation seen in hand specimen.)

Under the microscope the irregular interlocking quartz grains frequently exhibit a marked elongation in sections cut normal to the bedding. Undulose extinction often accompanied by incipient cracking is a common feature. Minute dusty inclusions, many of which are gas-liquid inclusions, are always present and appear to be arranged in lines normal to the direction of elongation of the grains (figure 3A). These appear to be directions of tension joints ("ac joints") as described by Fairbairn (1937, p. 89), although this cannot be verified until fabric analyses of these rocks are made.

The presence of abundant chrome muscovite inclusions in the quartz grains is the most remarkable feature of the upper quartzites. These are all arranged in parallel orientation as shown in figures 3 (A) and (B). In sections normal to the bedding the mica appears in innumerable minute parallel rods. Sections parallel to the bedding (figure 3B) show that the minute mica flakes are all euhedral and the marked lineation noticed in the hand specimen becomes evident under the microscope in the elongation of these flakes in a common direction.

The mica, in hand specimen, is a pale bluish-green colour, but under the microscope it appears colourless, except in thicker sections, when it has a bright light greenish colour with pleochroism :—

X pale bluish ; $Y = Z$ pale yellow-green ; absorption $X \leq Y = Z$.

$\beta = 1 \cdot 606$; $(-)2V = 31°–33°$; Dispersion distinct $r > v$.

A determination of the Cr_2O_3 content of mica isolated from a narrow band (2 inches wide) of chrome mica in one of the Lower Quartzites gave—

Cr_2O_3 0·22 per cent.

This is considerably lower than the Cr_2O_3 of the normal chrome muscovites quoted by Doelter (1917, p. 428). Of the six analyses quoted, the lowest, Cr_2O_3, is 0·87 per cent, and it goes as high as 3·95 per cent in the original fuchsite from Zillerthal. Hutton (1940, p. 330B) has described a chrome muscovite containing 0·27 per cent Cr_2O_3 and has noted how even a very small chrome content is sufficient to produce a bright green colour in a thick flake of the mineral.

Partridge (1937, p. 457) has recently described a similar mica from Mashishimala, Transvaal. It carries 0·85 per cent Cr_2O_3 and Partridge considers that chrome muscovite is a better name for this mineral than fuchsite as it was previously termed. In its optics : Pleochroism X blue, Y yellowish green, Z bright green (bluish), $\beta = 1 \cdot 596$, $(-)\ 2V = 35°$; it agrees closely with the mica in the Toodyay quartzites. The chrome muscovite, according to Partridge, occurs quite commonly in the quartzites of the Swaziland System in South Africa and it is therefore similar in occurrence to the chrome-muscovite in the Toodyay quartzites.

The source of the chromium, which is so widely disseminated through these quartzites, is unknown—no chrome-bearing detritals have been noted in these rocks and no ultrabasic rocks (other than several small bodies younger than the quartzites) are known in the area. Partridge (1937, p. 459) has noted the presence of traces of chromium in minerals connected with, and contained in, the granites of North-East Transvaal, and also that the occurrences of chrome-muscovite are connected with the granite intrusions and are found only in close proximity to the granite—he concludes, therefore, that the chrome-muscovite is genetically related to the granite.

An interesting association of tourmaline with the chrome muscovite was noted in the quartzites in the Gorge at Key Farm—here a few platy crystals of tourmaline up to 2 cm. long, coated with the greenish mica, were found on the bedding surfaces of the quartzites. The tourmaline is a slightly chromiferous pale brownish schorl with $\epsilon = 1 \cdot 659 \pm \cdot 002$, $\omega = 1 \cdot 615 \pm \cdot 002$, containing 0·35 per cent Cr_2O_3. This occurrence seems to support the possibility that the chromium was derived from the granitic gneiss intrusions (or from its pegmatitic derivatives which are particularly numerous in the Gorge Creek locality at Key Farm, where the green muscovite is also more abundant than elsewhere).

(*b*) *The Lower Quartzites.*—There are six distinct bands in the lower part of the series. They are interleaved with sillimanite schist, hornblende schist (plagioclase amphibolite), and thicker granite gneiss bands.

They are mostly coarse grained types (average grain size 3 mm. or more) and have the same granoblastic structures as noted above, the main differences to the Upper Quartzite being the almost constant presence of felspar in the Lower Quartzites and its absence in the Upper Quartzite and the fact that the chrome muscovite in the Lower Quartzites is generally set between the quartz grains while in the Upper Quartzite it occurs as inclusions in the quartz.

Most hand specimens are very coarse sugary rocks with bedding planes sparsely coated with pale greenish chrome-muscovite. White turbid felspar is a common constituent, but is never present in amounts exceeding five per cent. It is usually a microcline, but rare grains of oligoclase and orthoclase are present. The felspar grains are much smaller than the quartz, reaching a maximum of about 0·5 mm. diameter—they are usually somewhat rounded, slightly turbid inclusions in the quartz, but the larger grains show a tendency to idiomorphism (figure 4A).

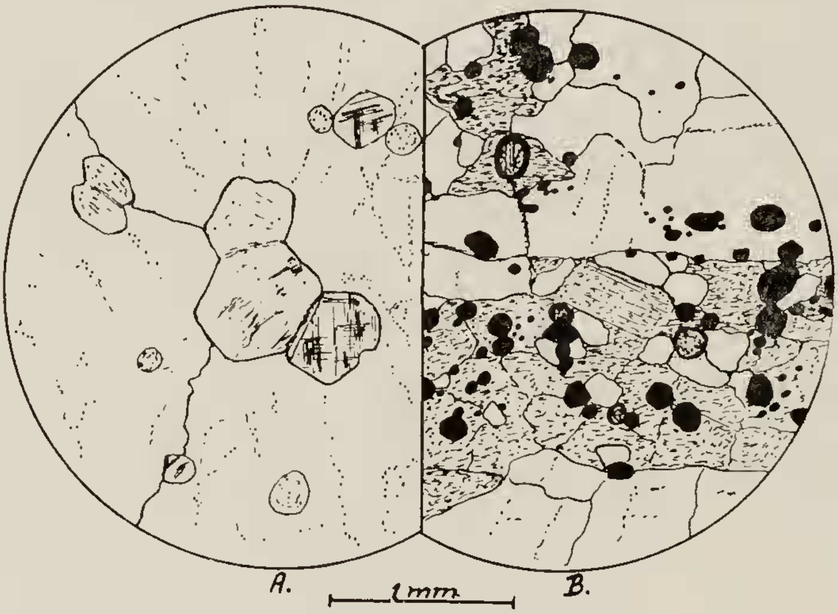

Fig. 4.

A. Felspathic quartzite, showing coarse granoblastic structure and tendency of larger microclines to assert their crystalline form.

B. "Heavy mineral" band in lower quartzite.

Minor detrital minerals occur sparsely in these lower quartzites—the most common species are rounded grains of zircon, magnetite and rutile. Pyrite in rounded grains with a thick rim of limonite is found occasionally—there can be little doubt, in view of the rounding of the grains, that the pyrite is an autochthonous constituent of the rock. The segregation of these "heavy" minerals into bands (figure 4B) has been previously noted.

(c) *The Origin of the Quartzites.*—The quartzites, then, are rocks of simple composition consisting almost entirely of quartz (95 per cent +). There can be little doubt that they were originally remarkably pure sands which have been completely recrystallised in the sillimanite zone. The coarse granoblastic structures, which have completely obliterated any sign of original clastic structures, testify to the high grade of metamorphism to which they have been subjected. In the absence of any foreign material, the only change in these rocks is the complete recrystallisation of the quartz. Hall and du Toit (1923, p. 77) in describing the very coarse quartzites at the base of the Bushveld

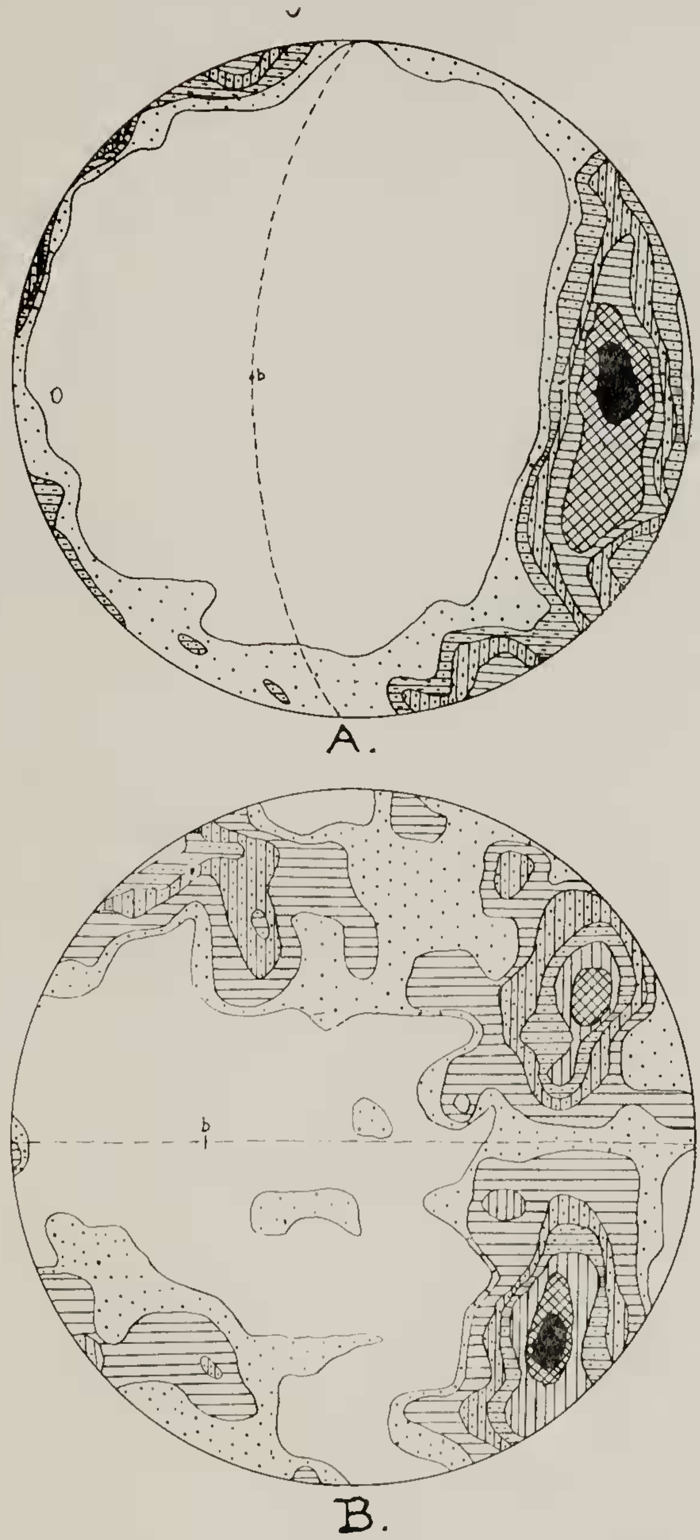

Fig. 5.

Fabric diagrams of the Jimperding quartzites (both rocks cut normal to the b-lineations).

A. Showing rare type of "Trener orientation" (Fairbairn, 1937, p. 70)—a marked elongated maximum coinciding with the "c" fabric axis. Dotted line is plane of foliation. Section perpendicular to marked lineation on bedding plane. Contours 7, 5, 4, 3, 2, 1.

B. Showing normal "ac" girdle with two prominent maxima, equally disposed to the "ab" plane. Dotted line is plane of foliation. Section normal to dip. No lineation apparent in handspecimen. Contours 7, 6, 5, 4, 3, 2, 1.

Complex near Pretoria, are of the opinion that the original purity of the sediment is essential for the formation of very coarse grained types of quartzites. The purity of the very coarse quartzites described above supports this theory.

That these rocks were deformed in an almost plastic state is seen in the minor drag folding which they exhibit—rocks from these dragfolded areas show no more cataclasis than in the less disturbed parts.

It is impossible to recognise any chronological succession in the quartzites as practically all sedimentary features have been obscured by recrystallisation.

(*d*) *The Fabric of the quartzites and its relation to the geological structure.*—Fabric analyses have been made of several quartzites, but in the absence of a set of geographically oriented specimens, no conclusions can be drawn from these analyses. They are quoted here to show that the quartzites have a well-marked girdle fabric (*i.e.*, are S-tectonites) and also because one of these rocks (figure 5A) exhibits a rare type of orientation (type " b " of quartz orientation, Fairbairn, 1937, p. 70)—the optic axes are concentrated in a direction normal to the bedding planes (*i.e.*, a prominent maximun lies in the direction of the " c " fabric axis). This maximum is somewhat elongated and spreads out into the typical girdle.

The other analysis (figure 5B) is a more normal type. In it there is a well developed " ac " girdle with two prominent maxima, equally arranged on both sides of the " ab " plane. This is a common type of fabric noted by Phillips (1937) in the Moine Schists of Scotland.

The analyses made, although insufficient to warrant any conclusions, serve to indicate that a fabric study of these rocks would probably yield much information regarding the tectonics of this region. One feature brought out is that the " b " fabric axis in the two analysed specimens coincides with the lineations on the bedding surfaces (*see* figure 2). Although no further fabric analyses have been made, as no universal stage equipment is available in Western Australia (the analyses of the two unoriented specimens described above were made in the laboratory of the Department of Mineralogy and Petrology at Cambridge under the direction of Dr. F. C. Phillips), a re-examination has been made of certain parts of the area with a view to determining the direction and pitch of these " b " lineations which, on the evidence of the two fabric analyses described above, are coincident with the " b " fabric axis (*i.e.*, the tectonic " strike " or tectonic axis, *see* Phillips, 1937, p. 587). These readings are indicated in figure 1, and show that there has been considerable cross folding on the main N.W. trending structure on axes trending N.N.E.

Although this structural study of the Jimperding quartzites is far from complete, sufficient has been done to indicate the desirability of continuing the work when universal stage equipment is available.

(2) *The Calc-Silicate Rocks.*

A rather interesting group of lime silicate rocks occurs in narrow lenticular seams at a constant horizon in the lower quartzites. The rocks lie just below the hornblende schist band and are of rather sporadic occurrence. They are characterised by the presence of grossularite, diopside, pale green amphibole, epidote, and sphene.

The first sign of the presence in the quartzite of lime-magnesia impurities is seen in the development of a pale greenish actinolite along with a little epidote in some felspathic quartzites (*e.g.*, specimen 1250*). Such rocks are

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* Numbers are the catalogue numbers in the collection of the Department of Geology, University of Western Australia.

coarse granoblastic structured types in which the amphibole occurs in pale greenish prisms with irregular terminations, either included in the quartz or set between quartz grains. It all has the same orientation and thus tends to give a banded appearance to the rock. Rarely, grossularite is noticed as a constituent of the felspathic quartzites (specimen 1248). Irregular shaped epidote granules and small lozenge shaped idioblasts of sphene are also included in the quartz. In these rocks the (Ca, Mg) silicates are only present as accessories.

Fig. 6.

Calc-silicate rocks.

A. Quartz-diopside-epidote-grossularite rock (1249), showing grossularite aggregates, with associated sphene, epidote and diopside. The clear areas are quartz xenoblasts.

B. Hornblende-diopside quartzite (15405) with grossularite (at top) and carbonate (centre and bottom).

An increase in the dolomitic impurity in the original sediment leads to the development of several types of rock :—

(*a*) Quartz-epidote-diopside-grossular rocks.

(*b*) Hornblende-diopside quartzites.

The former type (*e.g.*, specimen 1249) is a fine-grained, massive, pale yellowish, hornfelsic rock with a banded structure, due to the presence of parallel seams and lenses of vitreous quartz, one or two mm. in length. Under the microscope the constituent minerals are :—grossularite, epidote, diopside, quartz, and sphene.

The grossularite is the most abundant constituent forming 60 per cent or more of the rock. It occurs in aggregates of small idioblastic crystals of pale yellow colour. The irregular interspaces are occupied by clear unstrained quartz, towards which the garnet is always idioblastic, also drop-like quartz inclusions are common in the garnet. The garnet is all isotropic and has N = 1·765 (by immersion in oils) and is, therefore, a grossularite with slight admixture only of the other garnet molecules.

A pale yellow coloured epidote with very weak pleochroism is fairly abundant, generally in skeletal crystals which, except for the development of a good 001 cleavage and poorer 100 cleavage, are almost indistinguishable from the grossularite under ordinary light. The refractive index β close to 1·765, extinction $Z \wedge$ 001 cleavage = 30°, $\gamma - \alpha$ approximately ·042 and negative optical character, indicate an epidote with approximately 15 per cent Fe_2O_3 (Winchell, 1933, p. 313). These skeletal crystals often enclose idioblastic grossularite.

Diopside is not so abundant. It is a pale greenish variety in hand specimen, colourless in thin section. It occurs in a similar fashion to epidote, enclosing grossularite. The greater part of the diopside is confined to the quartzose portions of the rock, where it is idioblastic towards the quartz.

Sphene is an abundant accessory in cloudy irregularly shaped allotriomorphs usually surrounded by garnet. Accessory opaque iron ore occurs in several bands.

Quartz, the only other constituent, occurs in elongated xenoblasts and skeletal grains between the garnet crystals. There are no signs of any strain in the quartz.

The crystalloblastic order is: sphene, grossularite, epidote, diopside, and quartz. The microstructures are shown in figure 6A. An analysis of this rock, quoted from Simpson (1937, p. 32) is:—

SiO_2	50·68
TiO_2	0·96
Al_2O_3	12·63
Fe_2O_3	3·79
FeO	2·13
MnO	1·02
MgO	1·71
CaO	26·81
Alkalies	Tr.
H_2O+	0·35
H_2O-	0·26
	100·34

Judging from its high lime and alumina and absence of alkalies the rock was originally an impure siliceous and argillaceous limestone. The CaO, Al_2O_3, and SiO_2 have given grossularite, the entrance of some Fe_2O_3 has led to the development of epidote and the CaO with the small amount of MgO has given rise to diopside. The source of the titanium of the analysis is sphene, of which there is a small amount in the rock.

The hornblende-diopside quartzites are represented by a number of specimens in the collection of which 15405 shows all the characteristic features. Megascopically, it is a coarse-grained, dark green quartzite. Under the microscope, it is essentially a coarse granoblastic aggregate of quartz grains (2–3 mm. diameter) which carry poikiloblastic inclusions of pale greenish diopside ($Z \wedge c = 42°$ indicating the presence of some iron) and greenish amphibole. Aggregates of diopside, hornblende, grossularite, and a little carbonate occur between the quartz grains. The quartz (70 per cent of the rock) is xenoblastic towards all other constituents. It is all considerably strained and carries minute gas-liquid inclusions.

The amphibole, occurring in pale greenish sheaf-like aggregates, appears to be developing from the diopside which is occasionally seen as relicts in the amphibole prisms. The characters of this amphibole are:—

Pleochroism X pale yellow-green; Y deep olive green; Z bluish-green.

The absorption is $Y > Z > X$ and $Z \wedge c = 19°$, indicating that it is blue-green hornblende rather than actinolite.

Grossularite is present in small amount only, in irregular shaped, isotropic, yellow granules, always closely associated with the diopside. There is no epidote in 15405, but it occurs in similar rocks and possesses similar characters to that in specimen 1249 above.

15405 is the only rock in which any carbonate has been noted. It occurs in small xenoblastic forms, always with concave boundaries towards the other constituents. It is most abundantly developed in the vicinity of diopside and hornblende (figure 6B). The complete absence of twinning suggests that it is dolomite rather than calcite.

There can be no doubt that 15405 and related rocks are meta-dolomitic sandstones. Failure of the carbonate to react completely with the silica appears to indicate lack of sufficient aluminous and ferruginous impurities in the original sediment. The co-existence of quartz, grossularite, and calcite (or dolomite) indicates that these rocks have been developed by regional metamorphism under high pressure, for, if thermal metamorphism were responsible, then it would be expected that the remaining carbonate would have reacted with silica to give wollastonite.

The rocks described above are representative of the sparsely distributed calcareous seams in the original sandstones. They undoubtedly represent regionally metamorphosed impure dolomitic sandstones with a varying carbonate content. Kaolinic and ferruginous impurities have led to the formation of epidote and grossularite and a certain amount of iron has entered into the dolomite-quartz reaction producing diopside. In rare instances an insufficiency of impurities has inhibited the dolomite-quartz reaction. The grossularite in these rocks appears to have developed under conditions of regional metamorphism in the sillimanite zone. Tilley (1937, p. 372) has described the development of grossularite under stress conditions in the Loch Tay limestone of Perthshire. Here the grossularite, together with vesuvianite and diopside, first makes its appearance in the Almandine Zone. The Toodyay grossularite rocks show remnants of epidote, which in the Loch Tay limestones appears earlier than grossularite and disappears in the deeper parts of the Almandine Zone. The presence of epidote in the sillimanite zone at Toodyay, along with grossularite, indicates that epidote may, under certain conditions persist through the Almandine Zone.

(3) *The Mica Schists.*

These pelitic members of the Jimperding Series occur at two horizons. In the upper part of the series, a band of mica schist, approximately 250 feet thick, forms the upper limit of the series. This band is characterised by abundant andalusite. Another thinner band near the bottom of the series is characterised by sillimanite. Throughout the whole area the mica schists are considerably weathered, making examination o fthem somewhat difficult.

The lower mica schist can be traced from the south-east corner of the area almost to the western side. It is interbedded with quartzites and is everywhere contorted by small dragfolds consequent upon its having been folded between the two more competent quartzite beds. In the central part of the area and in the immediate vicinity of the townsite of Toodyay, it is considerably thickened by folding and it has been impossible in this crumpled portion to map all the minor folds.

The following types are developed amongst the mica schists :—

(*a*) *Sillimanite Schists.*—These are mainly two-mica schists with narrow psammitic bands. Slight variations have been noted and they are illustrated by the following descriptions of typical members :

(i) Quartz-biotite-sillimanite schists (*e.g.*, spec. No. 15638). These are finely schistose structured rocks consisting of bands composed almost entirely of fine acicular sillimanite, alternating with quartz-biotite bands which represent more ferruginous and psammitic layers in the original sediment. The fibrolite bands are occasionally distorted by a later growth of sillimanite in stout cross fractured prisms arranged at about 45° to the schistosity (figure 7A), indicating that a later thermal metamorphism was imposed on the earlier regional metamorphism which had developed the fibrolite. Muscovite (rare) also has a tendency to be arranged with its cleavages at about 45° to the schistosity.

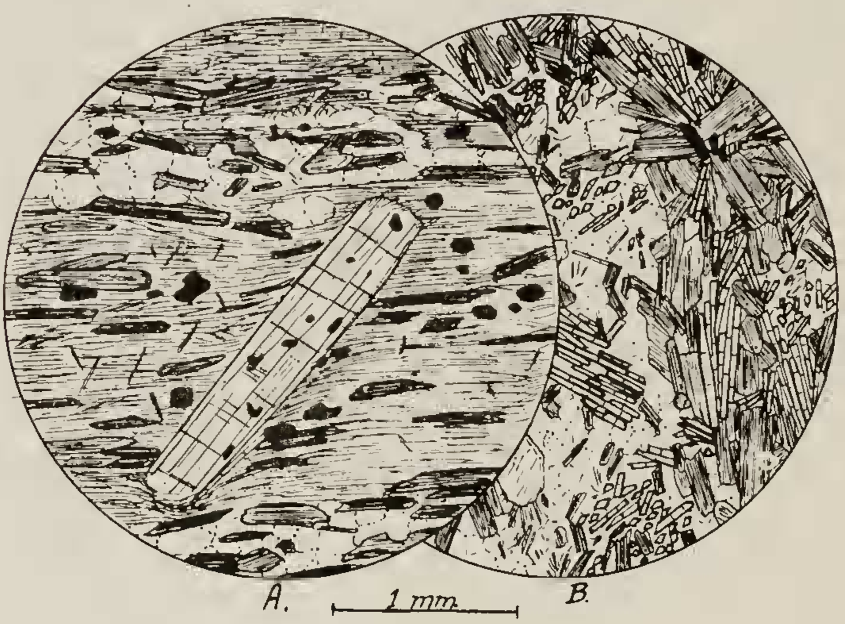

Fig. 7.

A. Sillimanite schist—bands of fibrolite with a little biotite, alternating with quartz-biotite bands. A later growth of sillimanite developed at about 45° to the banding. Note psammitic quartz-biotite bands.

B. Sillimanite-biotite-plagioclase granulite. No tendency to orientation of any constituents. The clear areas are fine granular plagioclase.

The fibrolite appears to be developing from biotite, the iron released in this change being represented by elongated grains of magnetite which occur most abundantly in the fibrolite layers.

(ii) Sillimanite-biotite-plagioclase granulite (*e.g.*, spec. 15678). Such rocks as these show the very interesting association of sillimanite with zoned plagioclase and myrmekite. In hand specimen the rock is fine-grained, greyish in colour with an irregular banded structure—fissile biotite bands alternating with granular quartz felspar bands. Under the microscope the structure is fine, even-grained granoblastic with lenticular areas rich in sillimanite and biotite with schistose structure. The approximate mineralogical composition is quartz 10 per cent, oligoclase 35 per cent, sillimanite 20 per cent, biotite 30 per cent, muscovite 5 per cent, and accessory magnetite and zircon, but in certain bands the sillimanite content rises to 70 per cent or more of the rock which thus becomes a valuable sillimanite ore.

In the psammitic bands both quartz and oligoclase are xenoblastic. The felspar is invariably zoned, the zoning being reverse gradational in character from $Ab_9\ An_1$ centre to $Ab_3\ An_1$ periphery ; twinning is seen in the central parts but the outer zone is generally untwinned. The outer zones of the plagioclase grains also carry numerous vermicular inclusions of quartz, forming a myrmekite-like structure. The development of this structure in the absence of microcline is interesting—it appears to be due to the growth of the plagioclase around crushed quartz spindles.

The sillimanite is in two generations :—(1) as fine acicular clusters, (2) stout cross fractured rods, the arrangement of which is unusual (figure 7B). In any section they appear to be arranged in bundles, some lying in the plane of the slice, others arranged normal to or at an angle with it.

The biotite is a deep reddish-brown lepidomelane in irregular shaped flakes with but little tendency to parallel orientation. In addition to inclusions of sillimanite there are numerous minute zircon inclusions, surrounded by pleochroic haloes.

Muscovite is in larger plates (1 mm.) carrying poikiloblastic inclusions of quartz and oligoclase. It is penetrated by sillimanite rods but is idioblastic towards the biotite.

Magnetite and zircon are the only accessories.

(iii) Cordierite-sillimanite schists (*e.g.*, specimen 15683). This specimen is the only metasediment of this area in which the presence of cordierite has been noted. There is no sign of schistosity in the rock, either in hand specimen or in the field occurrence. Constituents noted microscopically were quartz, biotite, muscovite, sillimanite, and pinite (after cordierite). The sillimanite is found as small tufts of needles closely associated with a deep reddish-brown biotite and radiating out into the neighbouring quartz. This variety is abundant and appears to be developing at the expense of the biotite. Sillimanite occurs in a second generation, in stouter rods haphazardly included in a pale brownish practically isotropic pinite (after cordierite) ; in section these pinitic areas measure up to 0·5 mm. diameter. There is no definite orientation in the micas. Plagioclase is absent.

The approximate mineralogical composition is :—biotite 35 per cent, sillimanite 25 per cent, quartz 25 per cent, pinite 10 per cent, muscovite five per cent, and accessory zircon and magnetite.

(*b*) *Garnet-biotite-plagioclase schist.*—The occurrence of garnet in the mica schists has only been noted in one place (15 chains S., 122 chains W. from datum). Here the garnets are found in a very sandy schistose rock, which, under the microscope, is seen to consist largely of zoned plagioclase. The rock is medium grained, schistose and granular in structure, with porphyroblasts of pink garnet up to 3 mm. diameter. The greater part of the rock consists of an equigranular completely recrystallised aggregate of plagioclase, quartz, and biotite with an imperfect schistose structure due to the subparallel alignment of biotites. The schistosity is interrupted by the idioblastic garnets which, during their growth, have pushed the biotite flakes aside. The crystalloblastic order is garnet, biotite, plagioclase, and quartz.

The biotite is a strongly pleochroic variety with X pale yellow, Y = Z deep brown, and refractive indices, $\gamma = 1{\cdot}638$ and $\alpha = 1{\cdot}591$. Zircon inclusions with pleochroic haloes are abundant. The plagioclase is an albite about Ab_9An_1 and shows slight normal gradational zoning. The centres of some of the crystals are slightly turbid with sericite-epidote alteration products.

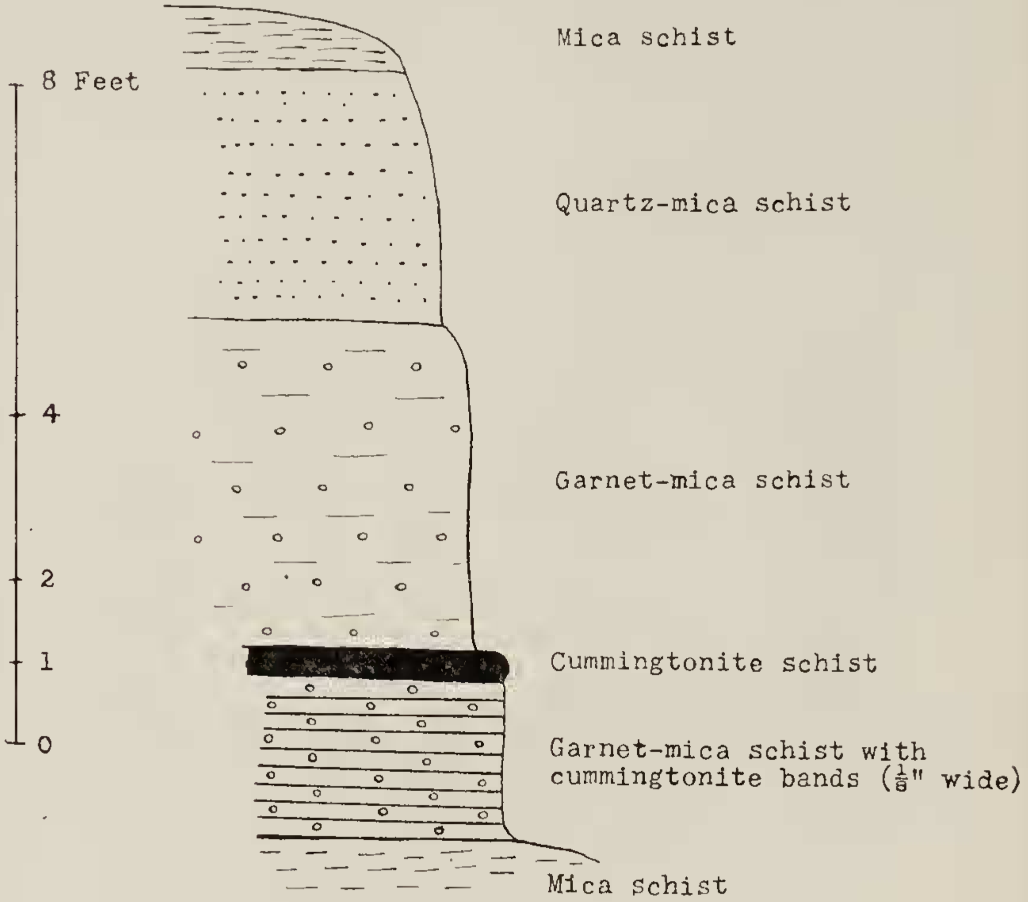

Fig. 8.

Sketch section of small waterfall at the head of Gorge Creek (15 chains S., 122 chains W., from datum), showing the relation of cummingtonite schists to the mica schists.

From the same outcrop as the garnet schist comes :—

(c) *Gedrite-cummingtonite-plagioclase schist.*—A typical specimen (19947) is a pale greenish-grey, fine grained banded rock—light greyish to white bands to ⅛ in. thick alternating with greenish-grey bands up to ¼ in. thick. Under the microscope there is a well-marked schistose structure and the minerals noted were gedrite, cummingtonite, plagioclase, and quartz.

The amphiboles occur in well-shaped prisms (often with poikiloblastic inclusions of plagioclase) up to 1·5 mm. in length. They all lie with their longer axes in the plane of schistosity, but appear to be of random arrangement in these planes since basal and longitudinal sections are present in approximately equal numbers in all sections cut at right angles to the schistosity. Both are pale clove-brown, not noticeably pleochroic varieties and are distinguishable only by the inclined extinction ($Z \wedge c = 17°$) of the cummingtonite as compared with the straight extinction ($Z = c$) of the gedrite. The former often shows lamellar twinning. The optics of the latter :—

> Pale clove-brown, non-pleochroic, $X = a$, $Y = b$, $Z = c$, (–) 2V large, $\gamma = 1 \cdot 667$, $\beta = 1 \cdot 659$, $\alpha = 1 \cdot 653$, indicate the aluminous variety, gedrite.

The light-coloured bands are composed of cummingtonite (with gedrite) + plagioclase + quartz, while the darker-coloured bands are much richer in cummingtonite and contain little or no quartz, and in some still darker bands green hornblende becomes an important constituent.

Specimens transitional in character between (*b*) and (*c*) are present in the same outcrop (see figure 8), and in these specimens narrow dark bands of garnet-biotite-plagioclase schist (often containing prisms of gedrite) alternate with light-coloured cummingtonite plagioclase rock.

A noticeable feature is that the amphibole in the biotitic bands appears to be all gedrite, whereas this mineral is subordinate to cummingtonite in the lighter-coloured layers.

All the above types (*a*), (*b*), and (*c*) are found in the lower band of mica schist. They have been derived from argillaceous sediments of variable composition ; plagioclase becomes evident in the slightly calcareous bands.

The various associations of sillimanite, biotite, quartz, plagioclase, and cordierite noted above are all well known. The gedrite-cummingtonite-biotite-oligoclase association is much rarer. Amongst the best known comparable rocks are :—

(1) The gedrite-plagioclasites of the Kragerö region, Norway, described by Brögger (1935, pp. 213–325). Although generally massive, schistose types have been described from this district. These rocks are considered to be derived from basic igneous rocks in a similar fashion to the gedrite (and anthophyllite)-cordierite rocks.

(2) The plagioclase-gedrite gneisses of the Nesodden Peninsula near Oslo, described by Brock (1926, p. 180) in which the association " quartz, plagioclase, biotite, garnet, gedrite " agrees very closely with that observed in the Toodyay rock. Brock considers that these rocks have been derived from leptites by addition of FeO and MgO.

(3) The garnet plagioclase amphibolites of Isopää, Kalvola, Finland, described by Eskola (1936, p. 475). Eskola in this paper describes a paragenesis of gedrite and anthophyllite, an association similar to that noted in the Toodyay schist, and he considers that the gedrite-cummingtonite-garnet amphibolite of Isopää has been formed by metasomatic replacement of basaltic agglomerates.

The gedrite-cummingtonite-biotite-plagioclase schist from Toodyay, from its interlamination with sillimanite schists and the rhythmic banding observed in the specimens appears to be a metasedimentary rock, derived probably from a thin bedded sediment such as an impure dolomitic shale.

(*d*) *Andalusite schists.*—These are confined to the uppermost pelitic band which outcrops in the S.W. portion of the area. The rocks of this band are quartz-muscovite schists with a variable biotite content. All the outcrops are highly weathered, the rocks appearing as yellow and reddish iron-stained schists. Simpson (1936, p. 11) has noted the occurrence of sillimanite (fibrolite) in these andalusite schists but it appears to be very rare, as I have noted the presence of sillimanite in one specimen only.

The andalusites show a constant variation in size and number throughout the band as shown in figure 9. At the bottom of the band the andalusites are very abundant—they project from the weathered surfaces forming 40 per cent or more of the exposed surface. The crystals vary in size up to 6 x 2 x 2 cms. The prism (110) is always well developed but the terminal faces are very poorly developed.

Traversing the band towards the south the andalusites become much smaller and less abundant and finally disappear, the rock then being a much weathered reddish muscovite schist which outcrops right up to the granite boundary.

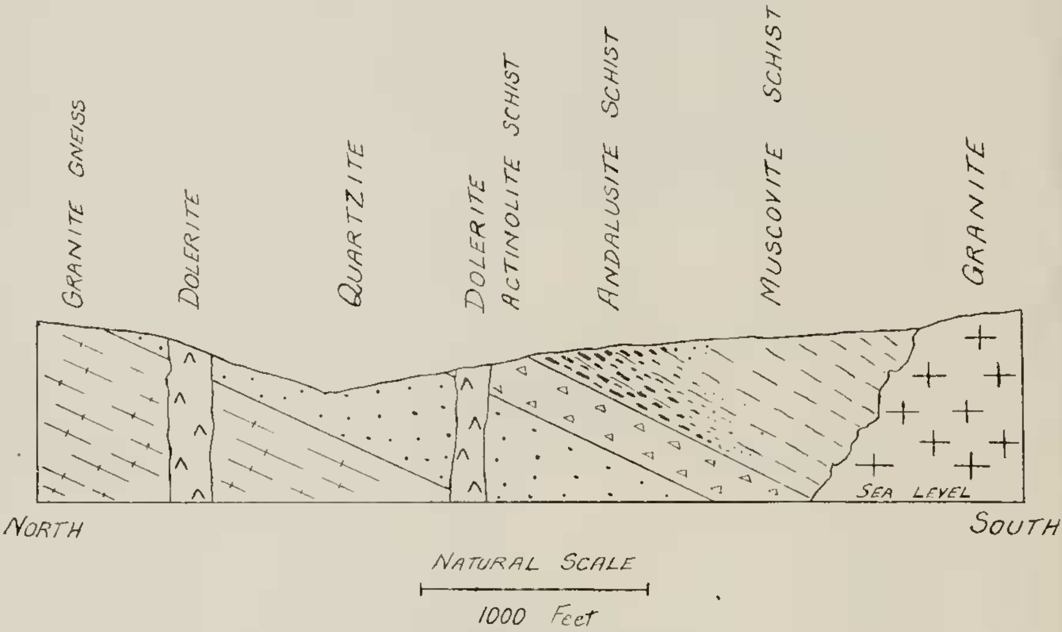

Fig. 9.

Cross section of upper mica schists showing distribution of andalusite.

The andalusites in the lower part of the band, as described and figured by Simpson (1928, p. 50), all show some alteration to muscovite :—

(1) On the periphery, to a coat of small muscovite plates.

(2) Within the crystals there is usually an irregular alteration to fine fibrous sericite. Most of the andalusites are clouded with carbon dust inclusions and show the typical chiastolite cross. In addition, we may note a peculiar feature shown by many of these andalusites : the arms and cleavages of the chiastolite cross are curved but the optic orientation remains constant throughout the whole crystal. This feature is similar to that shown by some staurolite and garnet crystals (Harker, 1932, p. 221) due to rotation during their growth.

The groundmass of these rocks is a quartz-biotite-muscovite schist. The biotite is completely weathered. It is interleaved with coarse platy muscovite. Quartz is abundant in smaller irregular shaped grains. Elongated lenticles of sericite are common. This material is similar to that developing in the larger andalusites and it appears to result from the shearing out of smaller andalusites in the base of the rock.

In one specimen this sericitic material is present in lenticular areas with irregular inclusions of quartz. The micas are deflected around these knots in a similar manner to the deflection around larger andalusite porphyroblasts.

The only other constituent is rare, well-shaped brownish tourmaline. In one specimen a few stout rods of sillimanite, arranged parallel to the foliation were noted, but this is the only sillimanite present in my specimens.

Proceeding in a southerly direction towards the granite, the andalusites become smaller and eventually disappear. Specimens from this part are similar to the groundmass of the andalusite schist but have a greater abundance of the fine fibrous sericitic bands and knots. Brownish tourmaline is present, but rare. This type of rock persists right up to the granite contact which cuts the schists off abruptly to the south. In a series of specimens collected throughout this band there was no apparent variation in the tourmaline content. The absence of any concentration of this constituent in the schists near the contact seems to negative the possibility that it was introduced from the granite. At the same time its constancy of character indicates a common source for all the tourmaline. Its origin is therefore somewhat doubtful, as it may be developed from constituents introduced from the intrusivo granite, or it may be original detrital tourmaline which has been recrystallised.

In considering the origin of the andalusite we naturally look first to the intrusive granite as the source of heat. The granite is intrusive because :—

(1) It transgresses the bedding of the mica schists.

(2) Several patches of schists up to 20 chains long x 8 chains wide have been noted which are surrounded by granite.

(3) It shows no foliation like the granitic rocks in the Jimperding Series.

There has been no apparent thermal alteration of the country rocks. As shown above, the andalusite is absent in the vicinity of the contact and, therefore, the genesis of the andalusite could only be attributed to thermal alteration by the granite if there were an increase in the pelitic constituents of the original sediment as it becomes more distant from the granite. Although no chemical analyses are available, microscopical examination shows that the composition is fairly constant throughout the band, and this rules out the granite as the agent which formed the andalusite.

The granite on its outer margin has suffered no chilling and is just as coarse-grained as it is at a distance of a quarter or half-mile from the contact. This suggests that the intrusion of the granite took place at some depth, into sediments which were themselves in a somewhat heated condition. The possibility of a faulted junction between the granite and schist must, however, not be overlooked.

The distribution of the andalusites indicates an accession of heat from below. There are several intrusive masses, below the andalusite schist (figure 9), which may have supplied the heat necessary for the development of andalusite :—

(1) The Upper Granitic gneiss.

(2) An ultrabasic sill now represented by a monomineralic actinolite schist.

(3) Dolerite dykes. These could not have effected the development of andalusite as they are post granite in age, whereas the development of andalusite was pre-granite.

Later retrogressive changes in the andalusite (*i.e.*, replacement by muscovite and sericite) are probably due to pneumatolytic alteration by vapours from the intrusive granite to the south, in a similar manner to the alteration of sillimanite to muscovite noted by Simpson at Clackline (Simpson, 1936,

p. 13). In addition there has been a considerable amount of shearing after the formation of andalusite, which in specimen 16743 is cracked and sheared out into lenticles consisting mainly of sericite but carrying relicts of andalusite.

(4) *Hornblende schists* (plagioclase amphibolites).

There are several different modes of occurrence of these rocks:—

(1) as well defined bands (average thickness 40 feet), interbedded with quartzites. All have been completely recrystallised and variable grain features, which may indicate the original nature of the mass (Cooke, etc., 1931, p. 49) have been obscured. These bands never transgress the bedding of the associated sediments, and they appear, in view of the great area over which they retain their constancy of character and horizon, to be basaltic flows which have been folded along with the associated sediments.

(2) as irregular shaped inclusions, usually of small areal extent, in the upper granitic gneiss. These are considered to be xenolithic bodies.

(3) coarser-grained xenoliths in the lower granitic gneiss. These are often veined with granitic material.

The two latter occurrences will be considered later in a section dealing with the xenoliths in the gneiss.

The schistose plagioclase amphibolites interbedded with the metasedimentary rocks are remarkably constant in character, consisting mainly of blue-green hornblende and acid plagioclase, with minor amounts of epidote, quartz, microcline, magnetite, sphene and apatite. The only variants of this type are diopside-plagioclase amphibolites of rather rare occurrence.

15437 is a typical example of the normal hornblende schist. It is a medium grained schistose rock consisting predominantly of hornblende. Epidote is an abundant constituent, and in hand specimen is seen to occur in pale yellow-green seams running parallel to the schistosity.

Under the microscope the rock has a well defined schistose structure, the hornblende occurring in irregular shaped prisms (average 0·5-mm. long), in parallel alignment. Other constituents are plagioclase, microcline, epidote, quartz, and sphene.

The hornblende prisms often carry small poikiloblastic inclusions of quartz and felspar. The hornblende is a common blue-green variety with X yellow to yellow-green ; Y olive to brownish-green ; Z bluish-green, and absorption $X < Z < Y$, $\beta = 1{\cdot}672$ and $Z \wedge c = 20°$.

The epidote is the pale yellow highly birefringent pistachite, usually confined to narrow bands parallel to the foliation. In the vicinity of epidote the hornblende is represented by a pale greenish bleached variety. Along joint cracks which are not coated with epidote the hornblende is also bleached —such joints traverse the hornblende crystals without dislocating them and are only evidenced by the presence of a narrow seam of more fibrous bleached hornblende which has the same optical orientation as the crystal traversed. There has clearly been some transport of material along these microscopical fractures, as seen by the occurrence of the same pale amphibole along the joint plane where it traverses quartz and felspar grains.

Two varieties of felspar are present, both xenoblastic and slightly elongated parallel to the schistosity. Albite, which is slightly turbid with fine granular epidotic and fibrous sericitic alteration, is most abundant. It rarely shows lamellar twinning, is not zoned, and its refractive index $\gamma \lesssim 1{\cdot}54$ indicates an albite with less than 10 per cent An.

The less abundant microcline is all water-clear and shows the characteristic cross hatched twinning. Microcline although rarely present in amounts exceeding 5 per cent is a constant constituent of these rocks.

The only accessory is sphene, in small imperfect crystals usually enclosed by hornblende.

This rock has been analysed as typical of these hornblende schists (Table 1, col. 1). It is an analysis closely resembling that of igneous rocks of the composition of quartz dolerite. An analysis of a dolerite from this area appears in column 4.

TABLE 1.

Analyses of Basic Rocks from the Toodyay Area.

	1.	2.	3.	4.
SiO_2	53·61	50·20	49·05	49·13
Al_2O_3	10·77	15·00	15·03	13·13
Fe_2O_3	2·21	3·83	3·16	3·65
FeO	9·02	8·93	9·08	8·95
MgO	6·92	6·04	6·96	7·64
CaO	10·04	10·65	10·47	11·84
Na_2O	2·12	1·90	1·70	1·72
K_2O	1·54	0·07	0·95	0·16
H_2O+	1·62	1·62	1·43	1·72
H_2O-	0·17	0·07	0·25	0·04
TiO_2	1·05	1·06	1·07	1·27
P_2O_5	0·17	0·12	0·08	0·14
MnO	0·35	0·16	0·09	0·15
FeS_2	n.d.	n.d.	0·13	0·45
	99·59	99·65	99·45	99·99
Norms.				
Q	5·10	6·18	1·98	3·48
Or	8·90	0·56	5·56	1·11
Ab	17·82	16·24	14·15	14·15
An	15·57	31·97	30·58	27·52
di	27·30	16·41	16·68	24·88
hy	17·52	19·18	21·58	18·33
mg	3·25	5·57	4·64	5·34
il	1·98	2·13	2·13	2·43
ap	0·34	0·34	0·34	0·34
py	—	—	0·13	0·45

1. Schistose plagioclase amphibolite (15437), interbedded with quartzite, Toodyay, W.A.
2. Schistose plagioclase amphibolite (1241), xenolith in Upper granite gneiss, Toodyay, W.A.
3. Coarse granular quartz-plagioclase amphibolite (15441), xenolith in Lower granite gneiss, Toodyay, W.A.
4. Quartz dolerite (15424), dyke in metamorphic rocks, Toodyay, W.A.

All analyses by R. T. Prider.

Amongst the rocks forming this band there is, as previously noted, but little variation. Microcline may be absent and quartz may be more abundant than in the type rock. Iron ore rimmed with sphene, indicating its origin from ilmenite, is a common feature, although in the rock described above the usual central ore inclusion in the sphene is absent.

The most unusual variant of the plagioclase amphibolites is a type in which diopside finds considerable development. 15440 is typical—it appears in hand specimen to be a normal hornblende schist with narrow bands and lenticles (never more than 2 mm. wide) of light greenish diopside.

Under the microscope the constituents are hornblende, diopside, and plagioclase with accessory quartz, apatite, and sphene. The hornblende and diopside are concentrated into alternate bands (figure 10B) and appear to have crystallised independently. The hornblende has a much stronger absorption than that described above—it has X yellow-green ; Y brownish-green ; Z deep bluish-green ; and absorption X $<$ Z $\lesseqgtr$ Y ; $\beta = 1\cdot674$; and $Z \wedge c = 16°$. The diopside is in irregular equidimensional grains to 0·5 mm. diameter. They have no definite orientation, the longitudinal cleavage being arranged at various angles to the schistosity, indeed often normal to it. This mineral is a pale greenish variety with the (110) cleavage well developed, $Z \wedge c = 42°$, indicating the considerable iron content. The diopside is idioblastic towards both the plagioclase and hornblende. Plagioclase forms approximately 30 per cent—it appears in two generations (1) a very turbid indeterminable variety clouded with secondary fine granular zoisite—this variety is more or less confined to the hornblendic bands ; (2) a clear fresh plagioclase associated with the diopside bands. Fine lamellar twinning is occasionally developed and the small extinction (2° – 3°) in sections ⊥ 010 indicates an oligoclase. Slight normal gradational zoning is noticeable in some grains.

Fig. 10.

Pyroxene-plagioclase amphibolites.

A. Coarse xenolith in Lower Gneiss. Constituents: diopside (dotted), hornblende (paler coloured at junction with diopside), slightly turbid plagioclase, quartz.

B. Fine banded variety interbedded with quartzite. Constituents: hornblende in well defined bands, diopside (dotted), plagioclase.

Sphene and rare apatite are the only accessories. Iron ores are absent.

Another specimen belonging to this group has an "augen" structure—the augen are of diopside aggregates set in a plagioclase amphibolite ground in which the felspar is heavily saussuritised.

A specimen taken from the upper contact of the hornblende schist with the quartzite at a point 132 chains E. and 229 chains S. of datum, shows a gradation from normal plagioclase amphibolite, through epidosite to a diopside-plagioclase rock in which grossularite is present in small amount—this latter type is developed right at the contact.

The plagioclase amphibolite portion of the specimen is the normal type in which the felspar is very turbid with fine granular epidote. Following this is a narrow band (¼ inch) consisting predominantly of yellow epidote (pistachite) with a minor amount of pale greenish hornblende and quartz—the hornblende then decreases in amount leaving an almost pure epidote band (¼ inch) in which lozenge shaped sphenes are a notable constituent. In the outer part of this band grossularite is occasionally seen. Beyond this, the rock consists of epidote, slightly turbid plagioclase (Ab_9An_1) and quartz, the two latter occurring in micrographic intergrowth. On the outer limit of the specimen, the rock consists of diopside and saussuritised plagioclase with a little grossularite, sphene, and quartz. Were it not so clearly related to the plagioclase amphibolite, such a rock could conceivably have resulted from the metamorphism of an impure argillaceous limestone. The development of grossularite in this rock is interesting, as it has developed from the epidotic alteration of the original felspar.

The main features which elucidate the origin of these schistose plagioclase amphibolites are :—

(1) They occur interbedded with metasediments and never transgress the bedding.

(2) They are constant in character throughout the area. Rarely, more calcic diopside layers alternate regularly with layers of the normal amphibolite. A similar feature to this is seen in the Landewednack hornblende schists of the Lizard, Cornwall (Flett and Hill, 1912, p. 46).

(3) The refractive index ($\beta = 1 \cdot 673$) of the hornblende is indicative of hornblendes from epidiorites in the sillimanite zone (Wiseman, 1934, p. 394).

(4) In their chemical composition they are normal igneous rocks, such as would result from the crystallisation of a quartz dolerite magma.

These plagioclase amphibolites appear, therefore, to be metabasic igneous rocks, which formed either a sill or flow in the metasediments prior to the orogenic period, and have been folded along with the metasediments. In view of the complete recrystallisation, no evidence is available as to whether these were originally flows or sills.

(5) *The Granite Gneisses and the associated xenoliths.*

As described above, there are two bands of light coloured granitic gneiss developed in the area. The Upper and Lower Gneisses form bands estimated to be approximately 2,000 feet and 5,400 feet thick respectively. Mineralogically, there is but little difference between the two, although the upper band, in view of the greater abundance of microcline is somewhat the richer in potash. It has also suffered more crushing than the Lower Gneiss and is everywhere a typical augen gneiss with large "eyes" of microcline, surrounded by a granular quartz-biotite-microcline aggregate. The lower gneiss is essentially a fluxion gneiss, in many places a coarse porphyritic type with idiomorphic microcline phenocrysts (up to 1 inch long), which have a linear orientation due to flowage. Both gneisses are penetrated by late stage pegmatitic products of the granitic magma—these may be narrow sills or veinlets traversing the foliation, usually only a few inches wide.

The Upper Gneiss is constant in composition and structure throughout. In places the crushing has been so complete as to obliterate the augen structure and fine banded gneisses have resulted. Such rocks have elongated narrow lenticles rich in fine granulated microcline, alternating with long sill-like streaks of unstrained quartz, in which the quartz extinguishes as a unit.

The foliation in both bands conforms to that in the associated metasediments. In the case of the upper gneiss, the gneiss-quartzite contact is often a narrow crush zone, varying from a few inches to a few yards in width. The rocks of this zone are quartz-sericite schists, in which the quartz appears in elongated lenticles up to 1½ inches x ¼ inch x ⅛ inch with prominent cross fractures (tension joints)—these lenticles are elongated in the plane of foliation, but more elongated parallel to the strike than to the dip.

In both gneisses there is often an irregular folding and contortion of the flow layers rich in biotite, due to folding movements which were taking place contemporaneously with the flowage.

That the gneisses are of igneous origin cannot be doubted in the evidence presented by numerous xenolithic bodies of variable composition—some metasediments, others metabasic igneous. These will be described presently. In places at the bottom of the Upper Gneiss (notably in Poison Creek), the gneiss is discordant to the bedding in the quartzite and small offshoots traverse the bedding of the quartzite.

We will consider firstly the Upper Granitic Gneiss and its associated xenoliths.

(a) *The Upper Granitic Gneiss.*

The main characteristics may be summarised thus :—

(1) Augen gneissic structure is characteristic throughout.

(2) Ptygmatic folding is occasionally developed.

(3) With the exception of occasional small basic xenoliths, narrow lenticles of plagioclase amphibolite and irregular small biotite granulite xenoliths, the composition is fairly constant throughout.

(4) Microcline is the dominant felspar.

(5) Myrmekitic structures are developed in most types.

(6) Biotite is invariably chloritised and contains sagenitic rutile inclusions.

(7) Narrow veins of pegmatite and aplite are numerous.

(8) Garnet and the various aluminium silicates characteristic of metasediments are completely absent.

The main type of the Upper Gneiss is a microcline granite gneiss, but other minor types are occasionally noticed. The varieties of Upper Gneiss are :—

(i) *Biotite-microcline granite gneiss.*—These are medium-grained rocks with augen gneissic structure. The augen are of microcline up to 1 cm. x 0·5 cm., in an even-grained ground of quartz, felspar, and biotite, the latter in sub-parallel alignment. The quartz is in elongated ellipsoidal grains (5 mm. x 3 mm. x 1 mm.) showing greatest elongation parallel to the strike and lesser parallel to the dip.

Under the microscope the minerals observed were quartz, microcline, oligoclase, and biotite with accessory magnetite, apatite, muscovite, zircon, epidote, rutile, and myrmekite.

Microcline is most abundant, occurring in xenoblastic plates, usually, but not always showing peripheral granulation (Plate III, C). This granular microcline aggregate is comparatively coarse-grained and seems to be a protoclastic, rather than a cataclastic structure—this is supported by the absence of any cataclasis or marked strain in the associated quartz. The microcline may carry small inclusions of quartz and plagioclase, and in the latter instance myrmekitic intergrowths of quartz with the plagioclase are usually present.

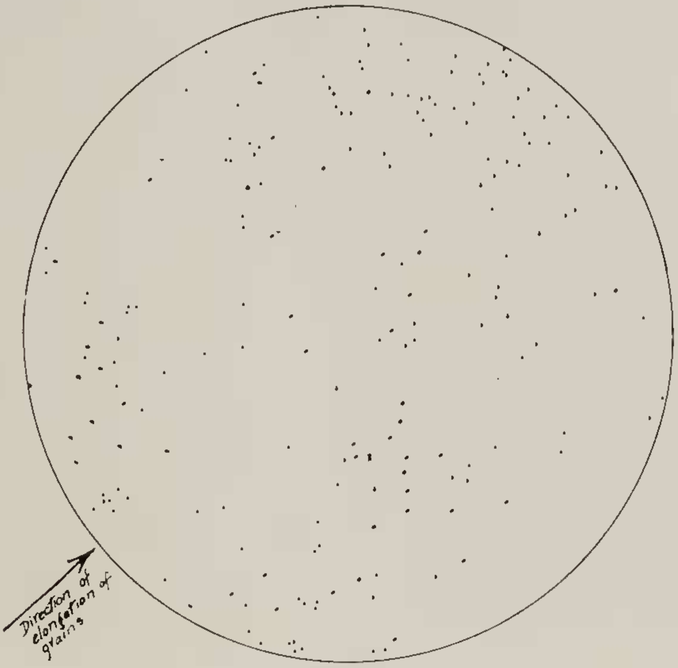

Fig. 11.

Fabric diagram of Upper granite gneiss. Plot of poles of optic axes of 200 quartz grains, showing the complete absence of any orientation in the quartz.

The quartz is in irregular shaped unstrained grains forming a constituent of the microcline mosaic and, as allotriomorphs, elongated parallel to the gneissic banding (Plate II, A and B, and Plate III, D), in which case it often includes parallel aligned biotite flakes. The quartz shows slight undulatory extinction but has not suffered any granulation and has been either :—

(1) of post tectonic crystallisation ; or

(2) original crushed grains, completely recrystallised into elongated xenoblastic forms.

A fabric analysis was made of a fine even-grained granitic gneiss, showing this marked elongation of unstrained quartz grains, but after the measurement of 200 grains no apparent concentration of the optic axes in any direction was noticeable (figure 11). Similar results were obtained from several other granite gneisses which were analysed.

It is interesting to compare this result with those obtained for several of the quartzites (figure 5. A and B), which show such a well-marked fabric. It would be expected that the gneiss would possess a fabric similar to the quartzites. The complete absence of any girdle in the diagram for the gneiss indicates that the quartz is of post tectonic crystallisation. This is verified by the observation, in some rocks, of granular microcline mosaics included in the quartz.

Plagioclase (10 to 15 per cent) is generally a slightly turbid and poorly twinned oligo-albite (Ab_9An_1) which is partly replaced by myrmekite when in contact with microcline—it is never zoned, and is invariably replaced in part by fine fibrous sericite.

Biotite which, on the average, forms 10 per cent of these rocks is of two types—(1) A strongly pleochroic greenish brown variety with minute sagenitic rutile inclusions. The flakes are well formed parallel to 001, but have ragged terminations. It is partially replaced by green chlorite, especially along the cleavage, leading to an intergrowth of these two minerals. (2) A bright greenish completely chloritised biotite, usually developed in contact with microcline and intergrown with epidote. The biotites often occur in small clustered aggregates—in the more crushed varieties they occur in well defined bands, curving around the lenticular granulated microcline aggregates.

Apatite is the most abundant accessory in stout idiomorphic prisms. Minor accessories are small zircons (with weakly pleochroic haloes) included in biotite, scattered grains of magnetite and epidote.

Specimen No. 1213, an even-grained type, has been analysed as typical of these granite gneisses, and the analysis appears in Table 2, Column 1. It is a typical granite, and the appearance of a little corundum in the norm is due to the slight secondary alteration of the felspars. There is insufficient excess alumina to suggest the possibility of a sedimentary origin for these gneisses. (Bastin, 1909, p. 461.)

TABLE 2.

Granite Gneisses from the Toodyay Area.

	1.	2.
SiO_2	71·85	63·28
TiO_2	0·25	0·83
Al_2O_3	15·00	14·56
Fe_2O_3	0·55	3·13
FeO	1·20	5·10
MnO	Tr.	0·09
MgO	0·42	1·70
CaO	1·52	3·51
Na_2O	3·67	3·66
K_2O	4·45	2·58
H_2O+	0·54	0·52
H_2O-	0·02	0·15
P_2O_5	0·11	0·45
	99·58	99·56
Norms.		
Q	29·52	20·40
Or	26·13	15·57
Ab	30·92	30·92
An	6·67	15·01
C	1·73	0·20
hy	2·58	9·74
mg	0·70	4·41
il	0·30	1·52
ap	0·34	1·01

1. Biotite-microcline granite gneiss (Spec. 1213), Toodyay, W.A. Analyst, R. T. Prider.
2. Biotite-oligoclase granite gneiss (Spec. 15389), Toodyay, W.A. Analyst. R. T. Prider.

(ii) *Microcline-granite gneiss.*—The mica is much less abundant than in type (i). These rocks are rare and occur in narrow seams. They consist essentially of microcline, quartz, plagioclase, and accessory biotite, and, therefore, probably represent an originally aplitic phase of the granite. The microcline is slightly microperthitic, and the less abundant plagioclase is a clear, finely-twinned oligoclase ($Ab_{85}An_{15}$). Such mica as is present is the same greenish-brown partially chloritised variety as described above.

(iii) *Biotite-oligoclase-granite gneiss.*—In this type, which is of rare occurrence, there is a much greater development of brownish biotite than in (i) above. The main felspar is oligoclase, and microcline is present to the extent of less than 10 per cent. The approximate mineralogical composition of a typical specimen (9577) is—

Quartz	20 %	by volume
Oligoclase (Ab_4An_1)	65 %	
Microcline	5 %	
Biotite	10 %	

Accessory rutile, zircon, and apatite.

The oligoclase is in subhedral crystals averaging 2 mm. diameter, with oscillatory normal zoning and average composition Ab_4An_1. Occasional plates of microcline are present and, when in contact with oligoclase, myrmekite is developed.

The biotite is a brownish, non-chloritised variety, but still carries the characteristic sagenitic rutile inclusions.

(*b*) *Xenoliths in the Upper Granitic Gneiss.*

(i) *Schistose plagioclase amphibolites.*—These are found in narrow irregular bands, varying from small stringers, several inches wide, which taper out quickly, to well-defined bands up to one chain wide which usually run parallel to the foliation of the gneiss. The occurrence in them of acid veinlets suggests that they are inclusions, rather than sheet-like intrusions, in the gneiss, and they often show a minute crumpling which accords with the view that they are xenolithic, rather than post gneiss intrusions, as there have been no major tectonic movements since the final consolidation of the granite gneiss.

There is little variation in these rocks and they are almost identical, both mineralogically and chemically, with the plagioclase amphibolites, already described, which occur interleaved with the meta-sediments. The main points of difference may be summarised :—

(1) Xenoliths in the gneiss have hornblende with a much stronger pleochroism :—X yellow-green ; Y deep olive green ; Z deep bluish-green ; and absorption $Y \geqq Z > X$.

(2) The plagioclase is more saussuritised and less abundant in the xenoliths.

(3) Microline is absent from the xenoliths and quartz more abundant.

(4) Magnetite, rimmed with sphene, spread out into trains parallel to the schistosity, is more abundant in the xenoliths.

A specimen of contorted hornblende schist (No. 1241) from a xenolith in the granite gneiss was analysed and the result is seen in Table 1, Column 2. The main points of difference from the previously described hornblende schists lie in the lower SiO_2 and corresponding higher alumina in the xenolith. The alkalies, especially potash, are also slighter lower. These features indicate the close resemblance of the two rocks and also indicate that there has been no addition of material to the xenoliths from the granite gneiss.

(ii) *Hornblendic schlieren.*—These small lenses in the upper gneiss were only noted in one place (40 chains N., 527 chains W. from datum). They are irregular shaped lenticles up to 12 inches wide, which are elongated parallel to the foliation of the enclosing gneiss.

That these schlieren are older than the intrusive granite gneiss is shown by the narrow granitic veinlets penetrating them, and also by the fact that small fragments of the xenolithic material are found in the enclosing gneiss.

The central portion of these inclusions is made up largely of a dark green, bladed hornblende, in crystals up to 0·5 cm. long, with occasional larger plates of a pale greenish pyroxene. Small white angular patches and veinlets of felspathic material are present. Near the edge of the xenoliths the rock becomes lighter in colour, hornblende becomes rarer, a pale greenish pyroxene taking its place. The enclosing gneiss is a fine granulitic microcline granite gneiss.

Under the microscope the fine microcline gneiss is seen to have pale greenish hornblende derived from the hornblendic xenolith, as its ferromagnesian. Approaching the contact the most noticeable features are (1) the increase in the hornblende content, (2) entrance of idioblastic sphene and colourless pyroxene, (3) decrease of microcline and corresponding increase of oligoclase. The felspars at the actual contact are considerably epidotised.

The xenolith itself is made up mainly of pyroxene, hornblende, and introduced quartz-oligoclase veinlets. The outer zone of the xenolith is rich in pyroxene (in large plates up to 4 or 5 mm. diameter), which under the microscope are seen to be fringed with pale greenish hornblende. The pyroxene in thin section is colourless, with 110 cleavages well developed and a marked parting parallel to 100 and less perfect parting on 010.

The properties $Z \wedge c = 42°$; $\gamma = 1{\cdot}705$; $\alpha = 1{\cdot}676$; $\gamma - \alpha = {\cdot}029$; biaxial $(+)$, and very weak dispersion. point to a diopsidic pyroxene with 20 per cent. of the hedenbergite molecule.

The amphibole which is clearly developing from the pyroxene is a pale greenish, somewhat fibrous variety, with an irregular coloration in the same crystal. Pleochroism is X yellow-green ; Y olive green ; Z bluish-green ; and absorption $X < Z < Y$. $Z \wedge c = 23°$. This is a common blue-green hornblende. It is usually developed where the pyroxene is in contact with oligoclase and rarely where in contact with quartz, the hornblende having apparently obtained its alumina from the felspar.

In the centre of the xenolith, although most of the diopside has been replaced by amphibole, cores of diopside in this mineral point clearly to its origin.

These xenoliths have been originally diopsidic rocks, now converted into rocks composed predominantly of hornblende. An anomalous feature is that the cores show considerably more alteration than the periphery. There has been a slight hybridisation of the adjoining granite (gneiss) giving rise to a fine-grained hornblende granite gneiss. This hybridisation of the granite is developed on a larger scale in the Lower Gneiss and this question will be considered more fully at a later stage.

(iii) *Biotite granulite xenoliths.*—These are much finer-grained and carry more ferromagnesians than the enclosing gneiss, in which they occur as irregular shaped elongated darker-coloured patches, in which the foliation approximates to that in the surrounding gneiss. All these rocks are alike petrologically, being composed of partly chloritised biotite, quartz, and oligoclase with accessory magnetite, apatite, and sphene. One specimen, however, shows a development of a deeply-coloured hornblende.

The boundaries of the xenoliths are sharp and there is no transitional hybrid zone. The structure is fine, even granular, schistose (figure 12). The plagioclase carries minute rodlike inclusions of recrystallised muscovite. It is rarely twinned but its refractive index, approximately equal to that of Canada balsam, indicates that it is an oligoclase.

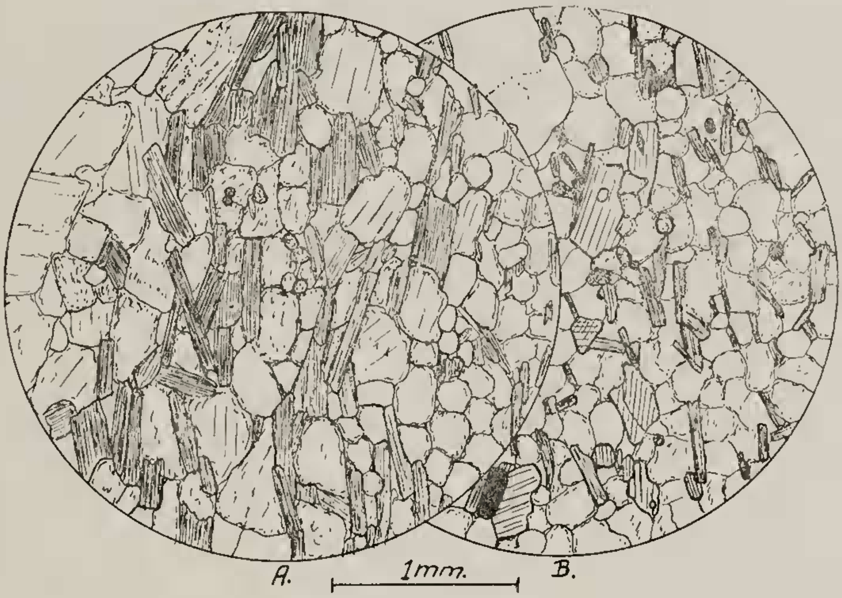

Fig. 12.

Biotite-quartz-plagioclase granulite xenoliths in granite gneiss.

A. No. 1220. Edge of xenolith. The left hand edge of the field is occupied by the coarse granite gneiss, the right hand portion by the biotite-quartz-plagioclase granulite.

B. No. 1221. Variety with deep greenish hornblende.

The biotite is a greenish-brown variety, altered along cleavages to chlorite.

The deep green hornblende present in one of these rocks tends to occur in small clots, often enclosing magnetite.

Accessories are apatite, magnetite, epidote, and sphene.

These rocks represent psammitic types of sediments, which with the admixture of a little calcareous material have at times developed hornblende and epidote ; they cannot be matched with any of the metasedimentary rocks in the Jimperding Series.

(iv) *Eulysitic rocks* (meta-banded ironstones).—Banded quartz-magnetite-grunerite rocks with affinities to the eulysites have been noted as enclosures in the Upper Gneiss in two places : (*a*) At 26 chains E., 40 chains N. of datum. This occurrence is in the form of a band, several chains wide, which can be traced for about 30 chains in a south-easterly direction. (*b*) At 92 chains W., 140 chains N. of datum. This occurrence is also a band in the gneiss, about 1 chain wide and can be traced for about 30 chains in a north-easterly direction. Both of these bands lie close to the bottom of the Upper Gneiss and are probably both part of the same horizon. The rocks from both occurrences are essentially the same, being magnetic banded rocks composed of varying proportions of quartz, magnetite, and grunerite. These rocks are similar to some occurring as xenoliths in the Lower Gneiss, which are described in a later section ((5) (e) (i)) of this paper.

(c) *Summary of Conclusions regarding the Origin of the Upper Gneiss.*

The main mass is constant throughout and is a normal biotite-microcline augen gneiss, derived from a porphyritic microcline granite. The presence of both sedimentary and igneous xenoliths and the occurrence of small transgressive apophyses in the underlying quartzite, point clearly to its intrusive character.

The gneissic banding was developed when the rocks had partially crystallised (*i.e.*, it is a fluxional foliation due to the alignment of the microcline), during which time protoclastic structures were developed. The final crystallisation of quartz took place after the tectonic movements had ceased.

The microcline granite was intruded as a thick sill which has produced no apparent thermal effects in the associated sediments which are in every instance quartzites. Such rocks, however, would not be expected to yield any information regarding the degree of thermal metamorphism induced by the granite. Felspathisation of quartzose rocks, about which a good deal has been written, is not developed in the Toodyay Area. It is not clear why the quartzites above this gneiss have different microstructures from those below the gneiss. If the granite were a sill we should expect them to be identical.

(d) *The Lower Granite Gneisses.*

These rocks, outcropping in the north and north-east parts of the area, vary from fine, even-grained, well-banded types, to coarse porphyritic granites in which the banding is visible only in a flow orientation of the microcline phenocrysts.

The well-banded varieties all have granoblastic structure with but little sign of granulation. A gneissic structure is evident in the sub-parallel orientation of the biotite and in the elongation of the felspar and quartz allotriomorphs in a common direction. In these finer-grained gneisses the quartz grains have an average index of elongation of about 3 : 1.

The mineralogical composition of the Lower Gneisses is fairly constant, irrespective of whether the rock is fine-grained or coarse porphyritic. The average composition by volume is :—

Oligoclase (Ab_4An_1)	30%
Microcline (slightly microperthitic)	30%
Quartz	30%
Biotite	10%

with accessory apatite, magnetite, and more rarely sphene and epidote.

Minor variations due to a greater abundance of biotite together with an increase of the proportion of oligoclase to microcline (as in the Upper Gneiss) have been noted. Also a hornblende bearing granite gneiss is developed by hybridisation of the granite by the hornblendic xenoliths which are present in some abundance.

The main point of difference from the Upper Gneiss lies in the general absence of cataclastic (or protoclastic) structures.

The microcline phenocrysts which in the Upper Gneiss are represented by lenticular "eyes" are here seen to be well-shaped, uncrushed crystals (up to 1 inch in length).

Biotite-oligoclase gneisses similar to those in the Upper Gneiss have been noted in narrow bands. Spec. No. 15389 is a type containing approximately 25 per cent. of a brownish biotite. It has been analysed as typical of these rocks (Table 2, No. 2). It differs from the microcline bearing gneiss in its higher iron and lower silica and potash content.

Under the microscope, oligoclase in subhedral grains up to 4 or 5 mm. diameter is the dominant constituent. It shows fine albite twinning, the lamellae often being slightly curved due to strain. A noticeable feature is that the quartz moulded on such a strained crystal shows no undulose extinction. The brownish biotite is in flaky aggregates winding around the larger oligoclases ; they feather out against one another and have been squeezed together by movements in the semi-crystallised magma. The microstructures recall in many ways the " round grained " gneisses of Glen Doll, Forfarshire (Harker, 1932, p. 298).

Apatite is a very abundant accessory, in small stout prisms, closely associated with the biotite rich bands.

These biotite-oligoclase granite gneisses appear to be the result of the crystallisation of the residuum squeezed off from the earlier formed microcline, thus containing a concentrate of biotite, oligoclase, and apatite.

(e) *Xenoliths in the Lower Granite Gneiss.*

Numerous oval areas of foreign enclosures varying from several yards in diameter, to elongated masses up to 10 chains in length have been noted in the Lower Gneiss. They are most abundant in the eastern part of the area (Plate I). Most are poorly exposed and, with several exceptions, the contacts with the enclosing gneiss are obscured by soil. The mapping, however, indicates that they are lenticular bodies completely surrounded by granite gneiss. The amphibolite enclosures are frequently traversed by quartz-felspar veins coming from the granite gneiss, thus establishing their pre-gneiss age. The longer axes and foliation of the enclosures strike parallel to the banding in the surrounding gneiss. There is considerable variety amongst these xenoliths and the main types will be considered separately as follows :—

(i) *Eulysitic rocks.*—These rocks are scarce in this area, but their occurrence is of interest since they bear similarities to rocks occurring as bands in the Bolgart greenstones to the north of Toodyay, and since they are representatives of the somewhat rare eulysites.

They are found in a small xenolith 10 chains S., 223 chains E. of datum (Plate I), entirely surrounded by gneiss. Nearby xenoliths are greenish " hornblendites."

Two rocks were collected from this locality and in view of their somewhat different character they will be described separately.

Banded quartz-magnetite-hypersthene rock (*Spec. No.* 15451).

This is a heavy, coarsely-banded type made up of bands (3 mm. wide) of silky lustred lamellar hypersthene, alternating with darker magnetite bands from 1 to 2 mm. wide. The rock is considerably weathered and iron stained, and its feeble magnetic character indicates that the magnetite has gone largely to fine granular martite.

The hypersthene is usually found with its longitudinal cleavage at about 45° to the banding. It has a poikiloblastic structure, enclosing both quartz and magnetite, and the original bedding has been preserved in the wide bands of magnetite and the thin parallel bands of fine granular ore which traverse the hypersthene (figure 13B). The hypersthene shows a fine lamellar structure. Cleavage is poorly developed, but there is a good parting on 010. Although brownish (due to slight weathering), the weak pleochroism is still visible. Its characters—X = a ; Y = b ; Z = c ; (−)2V = 83° ; γ = 1·765 : α = 1·745—indicate an iron rich hypersthene with approximately 85 per cent of the orthoferrosilite molecule (Henry, 1935, p. 223). Comparing the above data with those given by Henry (p. 223) for the iron rich hypersthenes, it will be seen that this hypersthene agrees almost exactly with the data given for the hypersthene in the eulysite from Mansjo, Sweden, which has (−) 2V = 83° ; γ = 1·769 ; α = 1·751. This is the most iron rich type described by Henry (containing 44·93 per cent FeO).

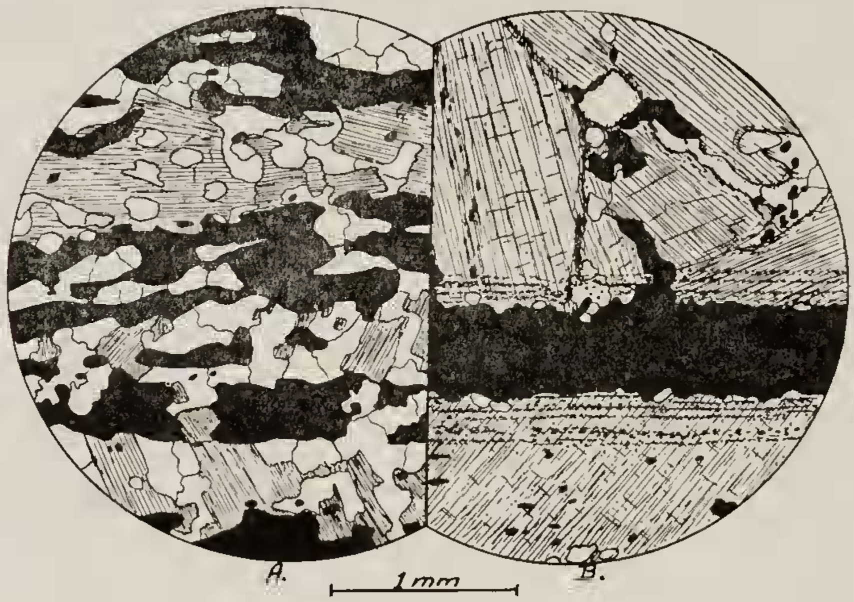

Fig. 13.

Banded eulysitic rocks.

A. Quartz-hematite-grunerite rock (No. 15452).

B. Quartz magnetite-hypersthene rock, showing original bedding preserved in the parallel trains of small magnetite grains included in hypersthene. The hypersthene is altering along its edges and along irregular cracks to a fine fibrous ferro-anthophyllite.

The hypersthene is altering to a more fibrous, highly birefringent amphibole, both around its edges and along irregular cracks. Some of the hypersthenes are completely replaced by this material. The optics of this amphibole are Z = c ; (−) 2V large ; γ = 1·687, and it is therefore a ferro-anthophyllite with approximately 60 per cent $FeSiO_3$.

Quartz and magnetite are the only other constituents with the exception of rare apatite. Both are closely associated and there is no sign of reaction between them. The magnetite is in bands up to 2 mm. wide and in trains of small grains (parallel to the bedding) included in hypersthene. In places, tongues of magnetite connect successive bands of iron ore. The almost non-magnetic character of the rock indicates that the magnetite has gone to fine granular martite, and this is confirmed by the cherry red streak of the dark bands. On the outer portion of the rock the reddish hematite can be seen replacing the magnetite, and the change throughout the rock is ascribed to oxidation due to weathering. A very different occurrence of hematite is seen in the other specimen from this xenolith which is described below.

The mineralogical composition (by volume) of the hypersthene rock is approximately—

Hypersthene	60 %
Ferro-anthophyllite	15 %
Martite (after magnetite)	15—20 %
Quartz	5 %
Apatite	Accessory.

Banded quartz-hematite-grunerite rock (15452).

This specimen is from the same locality as (*a*) above—the field relations between the two types are obscure.

It is a finely banded, even-granular rock, and consists of alternating dark coloured bands of recrystallised hematite and pale greenish quartz-amphibole bands varying in thickness from 0·5 to 1·0 mm. The specimen is non-magnetic—this, together with the deep red streak confirms the determination of the silvery grey, metallic mineral as hematite.

Under the microscope the structure is even-grained granoblastic gneissic, the hematite occurring in recrystallised grains and aggregates showing a marked segregation into bands (figure 13A)—quartz is often included in these aggregates and shows no signs of reaction with the hematite.

The amphibole and quartz form a granoblastic aggregate, the latter often occurring as poikiloblastic inclusions in the former. The amphiboles have a random orientation in the rock, although in particular bands they tend to show the same orientation throughout.

This amphibole is a pale greenish weakly pleochroic variety in irregular shaped prisms with lamellar structure. The prism faces are fairly well developed, but the terminations, whether in contact with quartz or iron ore, are irregular. It has good 110 cleavage and commonly shows multiple twinning on 100. The optics are $\alpha = 1\cdot635$; $\gamma = 1\cdot660$; $\gamma - \alpha = \cdot025$; $Z \wedge c = 15°$; (–)2V near 90. Opt. ax. pl. $\parallel$ 010.

The refractive indices indicate a cummingtonite with 42 per cent $FeSiO_3$, but the negative optical character suggests admixture of the actinolite molecule. Richarz (1927, p. 700) has described a similar amphibole from the Lake Superior District. It has $Z \wedge c = 15°$; $\gamma = 1\cdot680$; $\beta = 1\cdot668$; $\alpha = 1\cdot665$; $\gamma - \alpha = \cdot025$; (–)2V near 90° and composition :—

Al_2O_3	5·3%
Fe_2O_3	11·8%
FeO	22·4%
CaO	2·8%
MgO	5·4%

thus differing from grunerite in its high Fe_2O_3 and Al_2O_3 content. In its optics it closely resembles the Toodyay mineral which is probably an aluminous type of grunerite with admixture of actinolite molecules.

The origin of the banded eulysitic types.

The preservation of well marked banding in these rocks is indicative of their origin from sedimentary, bedded iron ores.

In their appreciable MgO content, and, in the case of type (b), the possible presence of CaO, the original rocks would appear to have been impure banded siliceous ankerite rocks rather than greenalites. In the hypersthene-quartz-magnetite rocks, the original carbonate must have been largely siderite with but small admixture of magnesite. The metamorphism has been effected under thermal, rather than regional conditions, as evidenced by the complete lack of orientation in the amphiboles and orthopyroxenes formed during this period.

In the case of the quartz-hematite-grunerite rock (*b*), it would appear that limonite was a constituent of the original quartz-carbonate sediment, and has, by re-crystallisation given rise to well crystallised hematite without any reaction with the quartz. SiO_2 has reacted only with the (Fe, Mg) carbonates to give rise to the grunerite. Such a quartz-limonite-iron carbonate rock is known amongst modern bog iron deposits (Van Bemmelen, 1900, p. 319).

The presence of considerable MgO and possibly CaO, and the variable proportions of quartz, iron ore, and amphibole (or hypersthene) throughout the rock seems to indicate that greenalite cherts were not the sediments from which the eulysitic rocks were derived, and while the sedimentary origin is clear, there is some doubt regarding the original character of the sediment, but it appears most probably to have been a banded limonite-iron carbonate rock.

(ii) *Calc-silicate rocks.*—Xenoliths of this type have only been noted in one place (114 chains N., 113 chains E. from datum). The rocks form a well defined band in the coarse porphyritic gneiss, running parallel to the strike of the enclosing rocks. The lime silicate rocks occur in bands and lenticles running through a band of white vein-like quartz.

The rock is similar to specimen 1249 (described earlier), differing only in the relative proportions of diopside and grossularite, and in being more siliceous. It has the following approximate mineralogical composition (Vol. %):—

Quartz 50 per cent, diopside 18 per cent, epidote 5 per cent, grossularite 25 per cent, amphibole and sphene 2 per cent.

Isotropic grossularite is the only idioblastic mineral, and it encloses diopside and occasionally quartz.

Diopside, which is not enclosed by grossularite, is altering to a fine fibrous colourless amphibole.

These rocks undoubtedly have the same origin as the lenticles of lime silicate rocks in the lower quartzites. They represent xenoliths of the Jimperding metasediments which have been caught up in the intrusive porphyritic microcline granite.

(iii) *Cordierite-anthophyllite rocks and related types.*—These rocks are found in a large xenolith in the granite gneiss at a position 236 chains E., 177 chains S. from datum. The occurrence is more or less circular in shape and about 5 chains in diameter. It consists largely of anthophyllite-hypersthene-pleonaste rocks, but several other types, viz., cordierite-anthophyllite and biotite-clinochlore-anthophyllite rocks are found here.

These rocks have been fully described elsewhere (Prider, 1940), but the chemical analyses are repeated here in Table 3. The conclusion regarding the origin of these anthophyllite-hypersthene-spinel rocks is that they were derived from a hypersthenite magma contaminated by aluminous material. The cordierite-anthophyllite assemblages were developed from the spinel hypersthenites during the period of intrusion of the granite gneiss, by the addition of silica from the granite magma.

TABLE 3.

Analyses of cordierite-anthophyllite rocks and related types from Toodyay, W.A. (quoted from Prider, 1940, *p.* 377).

	1.	2.	3.	4.
SiO_2	30·91	30·83	33·20	49·73
Al_2O_3	21·36	20·47	19·75	12·70
Fe_2O_3	19·97	9·23	3·36	4·56
FeO	—	11·28	13·23	12·27
MgO	23·57	16·10	21·57	16·59
CaO	Tr.	Tr.	*Nil*	Tr.
Na_2O	*Nil*	0·36	0·24	0·40
K_2O	*Nil*	5·18	0·22	0·54
H_2O+	2·58	4·87	8·43	2·77
H_2O-	0·90	0·42	0·10	0·12
TiO_2	1·66	0·70	0·06	0·21
P_2O_5	Tr.	nd.	nd.	Tr.
MnO	0·16	0·07	0·14	*Nil*
Cr_2O_3	0·17	*Nil*	*Nil*	*Nil*
	101·28	99·51	100·30	99·89

1. Olivine-spinel-anthophyllite-hypersthene rock, Toodyay, W.A.
2. Biotite-clinochlore-magnetite-corundum rock, Toodyay, W.A.
3. Corundum-spinel-anthophyllite-cordierite-clinochlore rock, Toodyay, W.A.
4. Biotite-cordierite-anthophyllite rock, Toodyay, W.A.

(iv) *The Amphibolite Xenoliths.*—Amphibolites, varying from almost pure hornblende rocks to quartz-plagioclase amphibolites in which the felsic minerals are in excess of hornblende, are the most abundant xenolithic types in the lower gneisses. They are found in lenticular masses, measuring up to 10 chains long x 3 chains wide, and in thinner bands which may be traced for greater distances. The elongation and lamination in the amphibolites are parallel to the strike of the enclosing gneiss. The occasional presence of narrow sill-like veinlets from the granite gneiss at the edges of the amphibolite masses indicates the intrusive character of the gneiss. There has, in some instances, been a considerable hybridisation of the granite gneiss, which has been changed from its normal character into a more basic hornblende granite gneiss.

These amphibolites comprise a number of types which are illustrated by the following description of typical members :—

Quartz-plagioclase amphibolites.

These vary from medium-grained dark coloured rocks with a visible lamination (15438). to types with a more granular structure in which no lamination is visible (*e.g.*, 15444).

The former are darker and more granular than the hornblende schists described earlier in this paper. The non-foliated granular type of amphibolite is the most common, and No. 15444 will be described as typical of this group. In hand-specimen it is a dark coloured granular rock with only a slight trace of parallelism of the hornblende which is the dominant constituent. It is a dark green variety in well shaped prisms 1 mm. in length, the interspaces between these prisms being occupied by light coloured fine granular felsic material.

Under the microscope the structure is granoblastic, and the rock is made up of brown-green hornblende (65 per cent), saussuritised plagioclase (15 per cent), clear oligoclase-andesine (10 per cent), quartz (10 per cent), with accessory epidote, magnetite, and sphene. The amphibole is idioblastic (figure 14A), in prismatic forms up to 2 mm. in length, usually clustered together, these groups being separated by finer granoblastic quartz-plagioclase aggregates.

Some of the hornblende has a poikiloblastic structure carrying rounded inclusions of quartz, magnetite, and, more rarely, plagioclase. It is a much deeper coloured variety than that developed in the hornblende schists interbedded with the quartzites, and has pleochroism :—X yellow-green ; Y dark olive green ; Z deep bluish green ; and absorption $X < Y \geqq Z$, $\beta = 1 \cdot 675$. Both quartz and plagioclase are xenoblastic. Two varieties of the latter are present in approximately equal amount (1) a completely saussuritised variety, and (2) a clear rarely twinned variety often showing slight zoning. It is an oligoclase-andesine near Ab_7An_3.

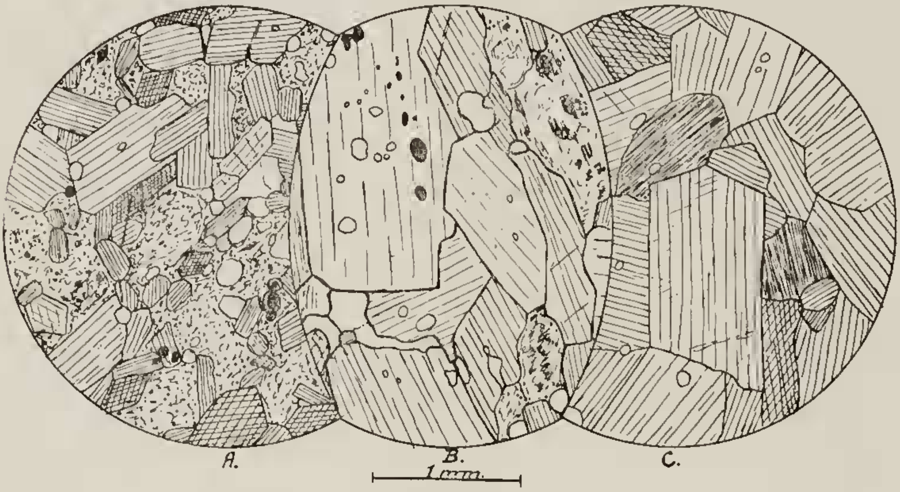

Fig. 14.

Amphibolite xenoliths in the Lower Granite Gneiss.

A. Medium grained plagioclase amphibolite (15444). Constituents are: hornblende, turbid plagioclase, quartz, magnetite with rims of sphene.

B. Coarser amphibolite (15441), showing poikiloblastic inclusions of quartz and magnetite in hornblende.

C. "Hornblendite"—Rare poikiloblastic inclusions of quartz in the hornblende.

Magnetite is the most abundant accessory and is invariably rimmed with sphene indicating its origin from ilmenite. Epidote and apatite are rarer accessories.

In coarser grained varieties (*e.g.*, 15441), the felspar is completely replaced by a fine granular sericite-epidote aggregate, and the larger, more abundant hornblende plates show a well developed poikiloblastic structure (figure 14B) with inclusions of quartz and magnetite, the latter often with a narrow rim of yellow highly birefringent epidote.

"*Hornblendites.*"

With a decrease of the quartz-felspar content the quartz-plagioclase amphibolites pass into almost pure hornblende rocks in which the only other constituent is an occasional small grain of quartz. 15436 is an example—in hand specimen it is made up of a granular aggregate of hornblende (figure 14C), noticeably lighter in colour than in the above types. Under the microscope many of the hornblende prisms carry small rounded poikiloblastic inclusions of clear quartz. Rare felspar is evidenced by the occurrence of small patches of fine granular epidote.

Pyroxene-plagioclase amphibolites.

These rocks are similar to the quartz-plagioclase amphibolites with the addition of a pale greenish diopside. They are like many of the hornblendic rocks of the Lewisian of Scotland.

No. 15445 is typical (figure 10A). It is coarse, even-grained, granoblastic, with no tendency to gneissic structure. The constituents are hornblende (60 per cent), diopside (25 per cent) and oligoclase (15 per cent), with accessory quartz and apatite.

The hornblende, in plates to 3 mm. diameter, sometimes moulded around diopside, is a brownish-green variety similar to that in the quartz-plagioclase amphibolite. It is noticeably paler in colour at its junction with the diopside. Poikiloblastic quartz inclusions are common.

The pyroxene is a pale greenish diopside with $Z \wedge c = 38°$. It has a curious mottled appearance due to small platy inclusions of pale green hornblende, which appear to be developing at the expense of the diopside.

The felspar is an oligoclase (Ab_4An_1) with fine albite twinning, occurring in subhedral to anhedral grains which are, in places, associated with hornblende in a sub-ophitic fashion.

Apatite, in euhedra averaging 0·2 mm, is the most abundant accessory. Quartz is very rare.

Chemical Composition of the Amphibolites.

Specimen 15441 (described above) was analysed as representative of the most widespread type. The analysis appears in Table 1, column 3. The similarity to the schistose plagioclase amphibolites 1 and 2 is at once evident. The igneous character of these rocks has been noted on an earlier page and need not be considered further here. Except for its slightly higher alumina and low lime and magnesia, this amphibolite analysis agrees very closely with that of the later dolerites (Table 1, col. 4) from this area.

The amphibolites, then, appear to be derived from basic igneous rocks approximating to dolerites or quartz dolerites in composition. Tilley (1921, pp. 98–116), who has described a number of amphibolite enclosures in the granite gneisses of the Southern Eyre Peninsula, South Australia, which are, in many ways, similar to those found at Toodyay, has outlined (pp. 108–109) the chemistry of the conversion of pyroxene to amphibole and little would be gained by repeating this here.

Where the hornblende becomes more abundant in these xenoliths its crystals become larger and apparently more aluminous at the expense of the plagioclase. Quartz persists, as a by-product of the amphibolitisation, even in the almost pure hornblendic types.

The pyroxene-plagioclase amphibolite xenoliths appear to represent completely recrystallised older basic rocks, such as occur in sill-like bodies of pre-tectonic age, interbedded with the Jimperding metasediments. The grain of these rocks has become coarser as a result of the recrystallisation of the amphibole. Basic xenoliths are often of fine grain (Joplin, 1935, p. 233) ascribed in part to the disruption of highly poikilitic crystals of hornblende. In the Toodyay gneisses the amphibolites have not suffered any such breaking up of the hornblende.

(*f*) *Hybridisation of the granite gneiss.*

There is a considerable development of quartz-oligoclase-hornblende gneisses in the Lower Gneiss as a result of hybridisation of the granite by basic inclusions. These types are well developed 80 chains N., 300 chains W. of datum, where the lower gneiss is seen to transgress the bedding of the hornblende schists and metasediments. The gneisses are of variable composition averaging :—

Hornblende	30 to 35 per cent (by volume).
Oligoclase	45 to 50 per cent.
Quartz	15 per cent.
Chloritised biotite	5 to 10 per cent.

Microcline is rare and the accessories are : magnetite, sphene, epidote, and patite. The plagioclase is usually much saussuritised but when determinable s an oligoclase (Ab_4An_1). The hornblende is a slightly deeper coloured variety han in the associated schists, and the biotite is the characteristic greenish chloritised variety, with sagenitic rutile inclusions. The hornblendes are often clustered together (fig. 15A) and may have a poikiloblastic structure. In specimen 10420, lenticular remnants of schistose plagioclase amphibolite are present in a hornblende-granite gneiss.

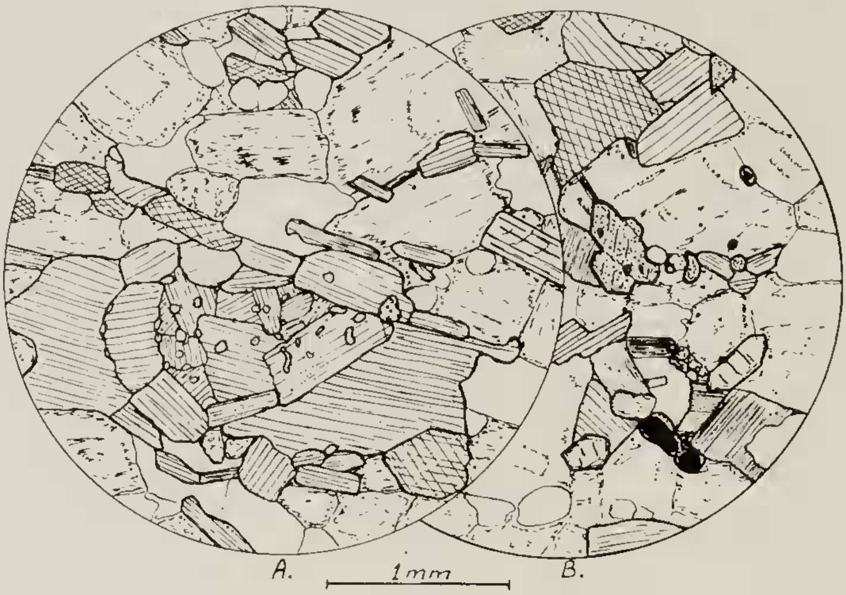

Fig. 15.

Granite gneiss—amphibolite hybrids.

A. 15640. Showing clotted aggregates of hornblende (often with poikiloblastic structure). The other constituents are turbid plagioclase and clear quartz.

B. 15397. Hornblende granite gneiss. Constituents are deeply coloured hornblende, somewhat fibrous pale greenish amphibole, oligoclase, quartz, idioblastic sphene (with central ore inclusions) and apatite.

A hornblende-granite gneiss (15397) from the vicinity of a coarse amphibolite enclosure has been analysed (Table 4, No. 2) and will be described in some detail. It is an even granular rock with a gneissic structure and it contains several sill-like quartz-felspar layers.

Under the microscope the constituents observed were : blue-green hornblende (20 per cent), oligoclase (55 per cent), quartz (20 per cent) with diopside, sphene, magnetite, apatite, and microcline as accessories. The structure is granoblastic with no tendency to parallel alignment of the constituents.

Hornblende, usually idioblastic, occurring in small lenticular clots is, in places, altered to a paler greenish fibrous amphibole. Xenoblastic oligoclase ($Ab_{87}An_{13}$), in slightly turbid grains averaging 1 mm. diameter, is the only felspar—it occurs in granoblastic aggregates with quartz and is frequently elongated slightly, parallel to the banding. The absence of microcline is unusual, but is explained by the fact that the microcline in the granite gneiss has crystallised early, forming large phenocrysts, and that specimen 15397 is the result of the reaction between the residuum and the basic xenoliths. Apatite, magnetite, and sphene are all abundant accessories ; the sphene is usually idioblastic and carries central inclusions of magnetite (fig. 15B).

The analysis of this rock, together with that of the microcline granite gneiss and coarse plagioclase amphibolite appears in Table 4. It is clearly intermediate between the other two types. The main discrepancy is in the alkalis, but this, as noted above, is due to the removal of the microcline phenocrysts from the magma prior to its reaction with the amphibolite.

TABLE 4.

Analysis of Hornblende Granite Gneiss (Col. 2) compared with Coarse Plagioclase Amphibolite (1) and Microcline Granite Gneiss (2).

	1.	2.	3.
SiO_2	49·05	64·16	71·85
TiO_2	1·07	0·74	0·25
Al_2O_3	15·03	15·12	15·00
Fe_2O_3	3·16	1·95	0·55
FeO	9·08	2·90	1·20
MgO	6·96	2·13	0·42
CaO	10·47	6·63	1·52
Na_2O	1·70	4·48	3·67
K_2O	0·95	0·20	4·45
H_2O+	1·43	0·67	0·54
H_2O-	0·25	0·04	0·02
MnO	0·09	0·18	trace
P_2O_5	0·08	0·32	0·11
FeS_2	0·13	0·15	nd.
Total	99·45	99·67	99·58

1. Coarse amphibolite xenolith (refer Table 1, No. 3), Toodyay.
2. Hornblende granite gneiss (No. 15397), Toodyay. Analyst, R. T. Prider.
3. Biotite-microcline granite gneiss (Table 2, No. 1).

Much more work, both field and laboratory, is required before any definite statement can be made regarding the origin of these acid hornblende bearing gneisses. So far as examined, however, they appear to represent a hybridisation of the intrusive granite gneiss.

(g) *Summary of the conclusions regarding the origin of the Lower Granite Gneiss and the associated xenoliths.*

The gneiss is essentially the same as the upper band but has not suffered such granulation—it is essentially a porphyritic granite, with flow orientation of the microcline phenocrysts. A less abundant biotite-oligoclase gneiss is considered to represent a more sodic phase of the main mass, which crystallised from residuum squeezed out from the earlier phenocrystal microcline. Late stage veins of garnet-aplite and pegmatite are developed from this magma.

Xenoliths of various types are described :—

(1) Eulysitic types developed from banded iron ores, probably sideritic and other carbonate types.
(2) Grossularite-diopside-quartz rocks derived from impure argillaceous limestones.
(3) Cordierite-anthophyllite rocks and related types derived from ultrabasic igneous rocks.
(4) Amphibolites, resulting from the reconstitution of basic igneous rocks.

B.—*The Younger Igneous Intrusives.*

(1) *The Granites.*

The later non-foliated granites are confined to the south-west part of the area where they are intrusive into the series described above. The granites are cut by later pegmatites, aplites, and quartz veins, which often penetrate the nearby metasediments and which are considered to be the source of the auriferous deposits found in the mica schists close to the granite.

The granites are always medium to coarse even-grained, remaining coarse-grained right to their contact with the metamorphic rocks, indicating that intrusion took place at some depth into already heated sediments. There is no sign of the porphyritic and foliated structures seen in the older granites occurring as bands in the Jimperding Series.

The later granitic intrusions are represented by three phases, which may may be described briefly as follows :—

(*a*) *The normal granites* are coarse textured rocks consisting of quartz, slightly perthitic microcline, sericitised oligoclase (Ab_4An_1, often with zonal alteration), abundant myrmekite, irregular chloritised biotite flakes with intergrowths of epidote, and accessory apatite and sphene. In their mineralogical composition these rocks are very similar to the older granite gneisses described above.

(*b*) *Garnet-muscovite granites* are even, fine to medium grained, allotriomorphic granular structured rocks made up of quartz, slightly perthitic microcline, oligoclase and muscovite, with accessory pink garnet (altered along irregular cracks to greenish biotite) and a little brownish biotite. These represent a hypabyssal phase of the granite and occur as dykes in the metamorphics close to the main granite mass.

(*c*) *Pegmatites, garnet aplites, and later quartz veins* represent the final phase of the granite intrusion. They are found in dykes and veins in both the granite and adjacent metamorphics. The pegmatites are coarse grained microcline and muscovite bearing types. in which the presence of molybdenite, columbite, and beryl have been noted—the two latter by Simpson (personal communication).

The garnet aplites are the fine grained equivalent of the garnet-muscovite granites. The prevailing texture is fine equigranular granitic, and the constituents are quartz, microcline, and oligoclase with accessory biotite (rare) and small pink garnets. The aplites often form a part of the pegmatite veins.

White quartz veins, representing the final ultra-acid phase of the granite, are fairly numerous in the metamorphics close to the granite. A flat dipping quartz vein in a roof pendant of mica schist in the granite has been proved to be auriferous, a test parcel (50 tons) of this ore mined several years ago yielding 15 dwt. gold per ton.

(2) *The Greenstones.*

(*a*) *Quartz dolerites.*—These are the latest intrusives into the Jimperding Series. They occur as dykes up to five chains wide, most of which trend a little W. of N., although there are several large dykes with an E.–W. trend. The geological map (Plate I.) shows the distribution of these dykes. They all belong to the same period of intrusion and no examples of one dyke being cut by another were found. This period of intrusion was much later than the last orogenic movements in this region and the doleritic rocks show no alteration other than those of deuteric character.

They are variable in grain from fine basaltic to coarse gabbroidal, and ophitic texture is characteristic except where obscured by extensive uralitisation of the pyroxene in the more acidic types.

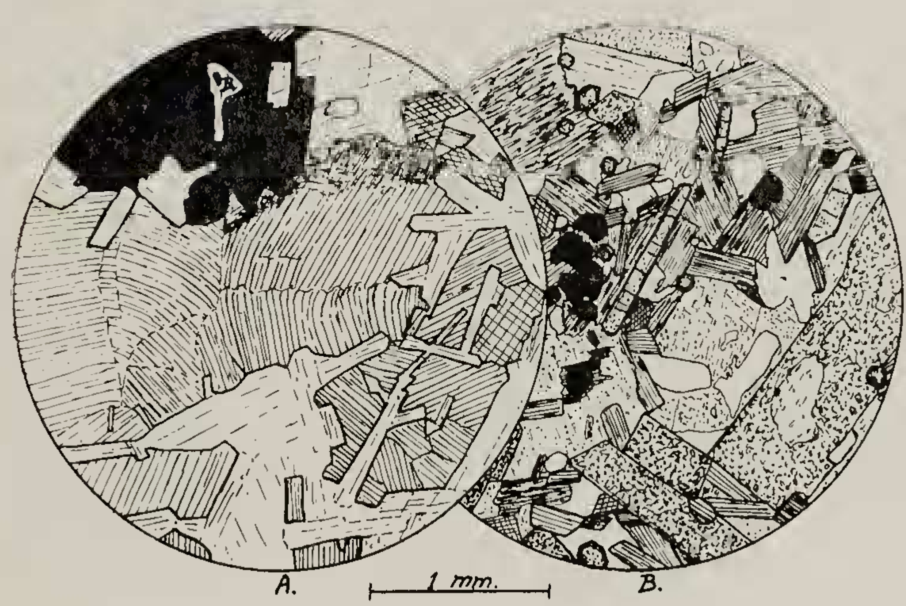

Fig. 16.
Quartz dolerites

A. Quartz rare. Both pyroxene and plagioclase are unaltered. The ophitic texture is well marked. The pyroxene cleavages are slightly curved and incipient fracturing is noticeable. A little primary brown green hornblende is seen in upper right in the vicinity of the end phase quartz. The iron ore is ilmenite.

B. End phase of the quartz dolerite magma showing a concentration of quartz and apatite. Fibrous uralite replaces pyroxene (upper left) and the idiomorphic plagioclase is highly saussuritised. The ferromagnesian is mainly a brownish "primary" hornblende.

The rocks vary from quartz-free dolerites made up of slightly brownish pyroxene and plagioclase (Ab_1An_1) with apatite and ilmenite as accessories, through quartz dolerites which usually show considerable uralitisation of the pyroxene, to more acidic types made up largely of plagioclase, uralitised pyroxene, primary brown-green hornblende, and quartz, with leucoxenised ilmenite and apatite as abundant accessories. The uralitisation of the pyroxene is definitely a deuteric process in these rocks because there are no later intrusives or earth movements which could have effected these changes, because it is developed much more extensively in types in which the end stage quartz has been concentrated, and also because both unaltered and highly uralitised rocks occur in the same dyke.

The microscopic characters of quartz dolerites have been so frequently and fully described that little space will be devoted to the description of the Toodyay quartz dolerites which do not differ in any way from the normal type of this rock. The only variations are in the proportion of micropegmatite and the degree of deuteric alteration.

The minerals developed in these rocks are :—

Pyroxene, which is always a pale brownish, non-pleochroic, monoclinic variety, of subhedral to euhedral development, usually penetrated ophitically by plagioclase. There is no zoning and only one type is present. Twinning on 100 is common. The extinction $Z \wedge c$ is 38–41° and 2V is somewhat variable in different grains from 42° to 48° (measured on the universal stage) and $\gamma = 1 \cdot 720$. The data indicate a pyroxene intermediate in character between pigeonite and the diopside-hedenbergite series. In some instances, the cleavages of the pyroxenes are bent and the crystals show incipient fracturing (fig. 16A). Alteration to a fibrous greenish uralite is common, proceeding from the periphery to the centre and often completely replacing the pyroxene.

Plagioclase is the most abundant constituent. It is in long columnar and lath-like crystals with well-defined edges in the prism zone and poorer terminal faces. Fine lamellar twinning, both albite and pericline, together with simple Carlsbad twinning are commonly developed. The main felspar is a labradorite about $Ab_{50}An_{50}$, but it almost invariably exhibits a gradational normal zoning, which in some instances has been to a periphery as sodic as $Ab_{80}An_{20}$, although the general range is from $Ab_{50}An_{50}$ to $Ab_{70}An_{30}$. In many instances the plagioclase is completely replaced by a fine granular saussurite and in such instances there may be a thin outer rim of sodic plagioclase. The sassuritisation, although generally irregularly distributed throughout the grains, seems to commence at the centre. Arborescent growths of a pale greenish weakly birefringent chlorite along cleavages and fractures of the plagioclase are very common. The chlorite appears to come from the fibrous uralitic coating of the pyroxene and its distribntion points to the migration of the end stage vapours and liquids along the cleavages of the earlier crystallised felspar.

Iron ores, mainly ilmenite, may occur in skeletal crystals as large as the largest pyroxenes. In some highly uralitised types it is altered to leucoxene (pale greyish in reflected light). Magnetite is present in one dyke to such an extent as to influence compass readings taken in its immediate vicinity. This magnetic feature of the dyke rocks was only noted in this one instance. It is probable, however, that much of the more common ilmenite has magnetite associated with it. The iron ore when in contact with felspar is usually rimmed with greenish fibrous chlorite. The only other ore mineral is pyrite, which is of rare occurrence, occurring in small cubic crystals.

Quartz varies from 0 per cent to 10 per cent. It is in angular grains filling the interstices between plagioclase prisms. In the more acidic types it commonly occurs in micropegmatite (along with a dusty acid plagioclase). Angular grains of micropegmatite up to 2 or 3 mm. diameter have been observed. It usually carries needle-like inclusions of apatite.

Amphibole is represented by two varieties :—

(1) A pale greenish, fibrous uralite with patchy coloration developing around the edges of pyroxene plates and frequently completely replacing that mineral. Although the edges become frayed, the ophitic intergrowth of plagioclase (usually saussuritised in the uralitic rocks) with these uralite pseudomorphs still remains visible.

(2) A brownish well-crystallised hornblende, only found in those dolerites which have abundant end stage micropegmatite. Although at times it appears to be of primary crystallisation, it often develops from the outer edge of the fibrous uralite, where this is in contact with the micropegmatitic mesostasis. It has pleochroism—X yellowish-brown ; Y brownish-green ; and Z bluish-green.

Biotite is a rare constituent only found in the most acid types, closely associated with the acid mesostasis.

Olivine is extremely rare, having been recognised in one rock only, where it is completely replaced by a dark greenish serpentine.

Apatite is the only accessory generally developed. It is in needles except in the most acid type, in which it builds stout euhedral prisms (fig. 16B).

Epidote, in addition to its occurrence in saussuritised plagioclase, often occurs in narrow veinlets cutting directly across all the above-named minerals.

Chemical composition of the quartz dolerites.

A typical example (No. 15424) showing only a very small amount of quartz and slight uralitisation was analysed and the result appears in Table 5, where it is compared with the average analysis of the Whin Sill rocks. The analysis of the Toodyay rock closely approaches the Whin Sill type, differing only in the somewhat higher lime and magnesia in the former.

TABLE 5.

Analysis of quartz dolerite from Toodyay compared with the average composition of the Whin Sill.

	1.	2.
SiO_2	49·13	50·52
TiO_2	1·27	2·39
Al_2O_3	13·13	13·76
Fe_2O_3	3·65	3·87
FeO	8·95	8·50
MnO	0·15	0·16
MgO	7·64	5·42
CaO	11·84	9·09
Na_2O	1·72	2·42
K_2O	0·16	0·96
H_2O+	1·72	1·51
H_2O-	0·04	0·76
P_2O_5	0·14	0·26
FeS_2	0·45	...
Others	...	0·69
	99·99	100·31
Norm :		
Q	3·48	
Or	1·11	
Ab	14·15	
An	27·52	
di	24·88	
hy	18·33	
mg	5·34	
il	2·43	
ap	0·34	
py	0·45	

1. Quartz dolerite (spec. 15424), Toodyay, W.A. Analyst, R. T. Prider.
2. Average Whin Sill Type (Holmes and Harwood, 1929, p. 539).

The resemblance of the Toodyay quartz dolerite to other doleritic rocks of the Darling Range near Perth which are considered to be comagmatic, has been noted in a previous paper (Prider, 1941, p. 46).

(*b*) *Ultrabasic intrusives.*—There are two types of ultrabasic intrusives in this area :—

(i) Completely metamorphosed types, now monomineralic tremolite and actinolite schists, occurring as sill-like intrusions into the Jimperding Series. The age of these rocks is unknown, but as will be shown below, they are probably earlier than the later normal granite.

(ii) Serpentine dykes. One only of these serpentine dykes has been noted in the area mapped. It is about $\frac{1}{2}$-chain wide and has the same trend as the quartz dolerites. Its age relations with the dolerites are not known.

(i) *Metamorphosed ultrabasic sills.*—Several narrow sill-like intrusions in the quartzite were noted in the vicinity of the R. W. Trig station. They are pale greenish, soft, schistose rocks composed almost entirely of a pale greenish actinolite with $Z \wedge c = 16^\circ$; $\gamma = 1 \cdot 650$; $\alpha = 1 \cdot 630$; (−) 2V large. This actinolite occurs in a felted network of fine prisms with the interstices filled with a pale green optically positive chlorite. Irregular-shaped grains of magnetite are scattered uniformly throughout.

Another rock (15641), also a sill in quartzite, consists largely of a felted mass of tremolite prisms with a ground of flaky antigorite dusted with magnetite inclusions.

A similar type is found just below the andalusite schist in the S.W. part of the area and this may be the intrusive which has led to the formation of andalusite. If so, the retrogressive changes in the andalusite, induced by the intrusion of the normal granite fixes these ultrabasic sills as pre-granite in age.

(ii) *Serpentines.*—These rocks are found in a narrow dyke $\frac{1}{2}$-chain wide and the only available specimen is from a point 28 chains N., 132 chains E., of datum.

It is a fine, even, dark greenish rock with a conchoidal fracture. Numerous minute silvery chlorite flakes are visible in hand specimen. Under the microscope it is seen to be made up of a very fine-grained aggregate of flaky antigorite ($\beta = 1 \cdot 57$) with occasional relict prisms of tremolite and a later development of chlorite flakes with magnetite inclusions coating the well-marked, crumpled 001 cleavages.

The chlorite is a very pale greenish variety and has $\gamma = 1 \cdot 595$; $\alpha = 1 \cdot 589$; $\gamma - \alpha = \cdot 006$; and $Z \perp 001$. This mineral, therefore, is a slightly aluminous iron-bearing antigorite.

The rock is a normal serpentine as shown by the following analysis of Specimen No. 15425.

SiO_2	40·33
TiO_2	0·28
Al_2O_3	2·75
Fe_2O_3	5·43
FeO	5·48
MgO	33·39
CaO	1·29
Na_2O	*Nil*
K_2O	*Nil*
H_2O+	10·16
H_2O-	0·10
MnO	0·14
P_2O_5	*Nil*
Cr_2O_3	0·10
	99·45

Analyst : R. T. Prider.

IV. ECONOMIC GEOLOGY.

Gold and the refractory minerals andalusite and sillimanite are the only minerals of economic importance which have been noted in this area.

(1) The *gold deposits* occur in the vicinity of Yinniding Creek in the south-western corner of the area mapped and have been described by Blatchford (1932), Forman (1935), and Prider (1934, p. 73), and require no further description here. The auriferous deposits appear to be genetically related to the younger non-foliated granite of the south-west part of the Area.

(2) *Refractories*—(*a*) *Sillimanite.*—Refractory clays derived from the alteration of sillimanite schists of the Jimperding Series have been worked at Clackline for some years (Simpson, 1936, p. 11; Matheson, 1938, p. 13). The sillimanite content of these clays is estimated to vary from 5 to 10 per cent of the rock.

In the Toodyay area, the metamorphism of the Jimperding Series has been effected under sillimanite zone conditions. Although sillimanite occurs in the micaceous schists throughout the area, the best sillimanite deposits noted during the survey were in the country lying to the north-west of Key Farm homestead, where there has been a thickening of the incompetent mica-sillimanite schists during folding. Although rapid variations in the sillimanite content are noticeable, the average sillimanite content over comparatively wide bands is high and in certain bands up to 10 feet wide, the sillimanite (mainly fibrolite) forms up to 70 per cent of the rock. This material constitutes a valuable ore provided the small muscovite-biotite content can be separated. Experimental work in this connection is at present in progress.

(*b*) *Andalusite.*—This mineral is developed in the uppermost band of mica schist in the south-western corner of the area. There does not appear, in the area mapped, to be any natural concentration of this mineral, sufficient to constitute an economic proposition. However, in the westerly extension of the andalusite mica schists, a mile or so west of the edge of the mapped area, in the headwaters of Mortigup Brook, considerable deposits of white weathered andalusite schist with abundant andalusite are exposed. These deposits are being exploited at the present time by a local company.

V. SUMMARY AND CONCLUSIONS.

A conformable series of metamorphic rocks has been described. It includes both sedimentary and igneous types. The former include interbedded sillimanite- and andalusite-mica schists, extremely pure quartzites, and occasional calcareous sandstones, now represented by calc-silicate rocks. All these rocks lie within the sillimanite zone. Rare biotite-plagioclase schists have been noted, in one instance carrying a considerable amount of gedrite and cummingtonite. This biotite-gedrite-cummingtonite-plagioclase schist is considered to result probably from the regional metamorphism of a somewhat dolomitic clayey sediment.

Interbedded with the sediments there are basic igneous rocks now represented by schistose plagioclase amphibolites, which have been derived by regional metamorphism, under sillimanite zone conditions, from tholeiitic rocks which may have been originally sills or flows. They are older than the first granite intrusion and have been folded along with the associated sediments.

Wider bands of granite gneiss have resulted from the intrusion of granitic magma into the above rocks. The period of intrusion coincided with the orogenic period, when the pre-existing rocks were altered to their present state. The granite, a porphyritic microcline type, was intruded under stress and presents a fluxional structure, which in the upper, more narrow band is emphasised by the slight shearing out of the microcline phenocrysts into microcline augen. Earth movements had practically ceased by the time that the granite had finally consolidated. Late stage aplites and pegmatites were associated with this period of intrusion. This intrusive granite has picked up fragments of the older rocks, comprising :—

(1) Plagioclase amphibolites and related types, derived from basic igneous rocks of doleritic composition.
(2) Altered ultrabasic igneous rocks, now represented by anthophyllite-hypersthene and anthophyllite-cordierite rocks.
(3) Metasediments in the form of banded eulysites (derived from banded iron ores) and biotite granulites (derived from psammitic sediments).

There is no evidence of any tectonic movements of later age than the granite gneiss intrusion.

Later these rocks were intruded by a granitic magma of similar composition to the earlier orthogneisses, together with its end stage products (aplites, pegmatites, and quartz veins). This granite has not effected any metamorphism of the older rocks other than the retrogressive alteration of pre-existing andalusite, by vapours advancing ahead of the intrusive mass. The intrusion of this later granite is considered to have taken place at considerable depth.

A later period of igneous activity is represented by dyke intrusions of quartz dolerite, which in their constancy of trend appear to have come up along joints or other lines of weakness, approximately parallel to the tectonic strike. Certain ultrabasic dykes are believed to be also post-granite.

The structure of the area, which is one of abnormal strike in the Western Australian shield, is interpreted as a major anticline, with its axis striking a little W. of N. and pitching to the south. This structure has a recumbent syncline on its eastern limb and is cross-folded on axes trending N.N.E.

The geological history of this region may be summarised thus :—

Early Pre-Cambrian (Kalgoorlie-Yilgarn Period)	1. Deposition of argillaceous and arenaceous sediments with a minor calcareous facies and with intercalated lava flows (or sills).
	2. Diastrophic period accompanied by intrusion under orogenic stress, of a porphyritic microcline granite. Main period of regional metamorphism. No orogeny after this period.
	3. Intrusion of end stage products of the microcline granite magma.
	4. Intrusion of the later granite. No further metamorphism.
	5. Intrusion of end stage products of the later granite. Period of formation of auriferous deposits.
Late Pre-Cambrian (Nullagine Period)	6. Intrusion of quartz dolerites.
	7. Erosion period.
? *Miocene*	8. Region reduced to a peneplain. Formation of laterite (Woolnough, 1930, p. 125).
Present	9. Erosion period to the present. The region is now a dissected, laterite-capped plateau.

VI. ACKNOWLEDGMENTS.

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Plate II.

Microcline granite gneiss.

A. Crushed microcline mosaic with sill-like quartz of post cataclasis crystallisation. Nicols crossed. X 20.

B. Later quartz veinlet cutting microcline phenocryst. Nicols crossed. X 25.

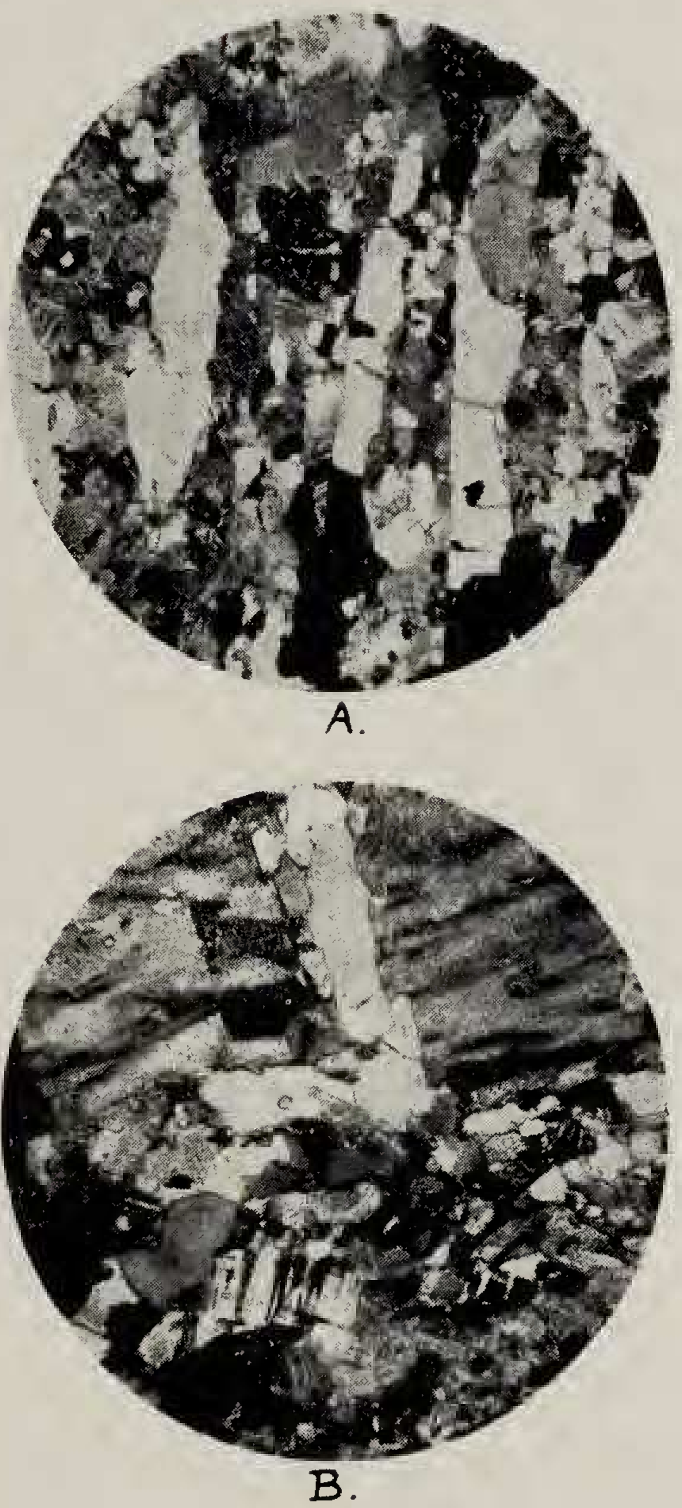

Plate II.

Plate III.

Microcline granite gneiss.

C. Small porphyroclast of microcline, with granulated periphery. Nicols crossed. X 25.

D. Finely granulated microcline granite gneiss. Elongated uncrushed quartz grains abundant. Nicols crossed. X 25.

C.

D.

Plate III.